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A PILOTED SIMULATOR INVESTIGATION OF GROUND EFFECT ON THE LANDING MANEUVER OF A LARGE, TAILLESS, DELTA-WING AIRPLANE

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16. Abstract

The influence of ground effect on the landing flare characteristics of a supersonic transport airplane (SST) was investigated in a fixed cockpit simulator. Simulations of an ogee-modified delta-wing F5D-1 airplane and a subsonic jet transport were used for evaluating the simulator and as reference configurations during landing comparisons.

Dynamic responses of the SST to seven different ground-effect models during controls-fixed and constant-attitude descents are also presented, followed by piloted subjective assessments. A summary of ground effects on delta-like wings is included in the appendixes.

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NOTATION

ANU,AND	airplane nose up, airplane nose down
a_z	vertical acceleration relative to wind axis (down, positive), ft/sec^2
C_D	drag coefficient, $\frac{\text{drag force}}{q_o S}$
C_{D_o}	C_D at zero angle of attack
C_j	jet engine thrust coefficient, $\frac{\text{engine thrust}}{q_o S}$
C_L	lift coefficient, $\frac{\text{lift force}}{q_o S}$
C_{L_o}	C_L at zero angle of attack
C_{L_f}	lift coefficient due to flap deflection
$C_{L_{trim}}$	lift coefficient for trimmed flight condition
C_m	pitching-moment coefficient, $\frac{\text{pitching moment}}{q_o S\bar{c}}$
C_{m_o}	C_m at zero angle of attack
CG,cg	center of gravity
CR	center of rotation
$\bar{c}$	wing mean aerodynamic chord, ft
d	perpendicular distance thrust line is below CG, ft
F_s	stick (column) force, lb
GE	ground effect
g	acceleration due to gravity, 32.2 ft/sec^2
h	altitude or height, ft

h_w	wheel height, ft
$\frac{h}{\bar{c}}$	ratio of quarter-chord (0.25 $\bar{c}$) height to mean aerodynamic chord
ILS	instrument landing system
I_X	rolling moment of inertia, slug-ft^2 (body axis)
I_Y	pitching moment of inertia, slug-ft^2 (body axis)
I_Z	yawing moment of inertia, slug-ft^2 (body axis)
i_T	thrust angle of incidence with body X-axis (up, positive), radians
K_h	ground-effect height factor
L	aerodynamic lift force, lb
L_{δ_e}	$\frac{q_o S}{mV}\left(\frac{\partial C_L}{\partial \delta_e}\right)$, 1/sec
M	aerodynamic pitching moment, lb-ft
M_{δ_e}	$\frac{q_o S\bar{c}}{I_y}\left(\frac{\partial C_m}{\partial \delta_e}\right)$, 1/sec^2
m	airplane mass, slugs
PR	pilot rating (Cooper scale)
p	roll angular velocity (right roll, positive), radians/sec
q	pitch angular velocity (ANU, positive), radians/sec
q_o	dynamic pressure, $\rho \frac{V^2}{2}$, lb/ft^2
r	yaw angular velocity (nose right, positive), radians/sec
S	wing reference area, ft^2
SJT	subsonic jet transport

SST	supersonic transport
$\frac{dT/W}{dV}$	speed-thrust stability, 1/knot
T	total thrust, lb
V	equivalent airspeed, ft/sec, unless otherwise indicated
V_a	approach speed, knots
V_s	minimum stall speed, knots
W	gross weight, lb
WT	wind tunnel
α	angle of attack, radians
γ_o	initial flight-path angle (up, positive)
Δ	incremental change
δ_e	elevator deflection (AND, positive), radians
δ_f	flap deflection, radians
ζ_{sp}	longitudinal short-period damping ratio
θ	pitch angle of airplane body axis relative to horizon (ANU, positive), radians
ρ	air density, slugs/ft^3
ϕ	angle of bank (right wing down, positive), radians
ω_{nsp}	undamped longitudinal short-period natural frequency, radians/sec
$(\dot{\ })$	derivative with respect to time, $\frac{d}{dt}$
$(\ )_\infty$	out-of-ground effect ("free air")

$$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$$

$$C_{m_{C_L}} = \frac{\partial C_m}{\partial C_L}$$

$$C_{L_{\dot{\alpha}}} = \frac{\partial C_L}{\partial (\dot{\alpha}\bar{c}/2V)}$$

$$C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial (\dot{\alpha}\bar{c}/2V)}$$

$$C_{m_q} = \frac{\partial C_m}{\partial (q\bar{c}/2V)}$$

$$C_{L_{\delta_e}} = \frac{\partial C_L}{\partial \delta_e}$$

$$C_{m_{\delta_e}} = \frac{\partial C_m}{\partial \delta_e}$$

$$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha}$$

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SUMMARY

The influence of ground effect on the landing flare characteristics of a tailless delta-wing supersonic transport airplane (SST) was investigated in a fixed-cockpit simulator. The characteristics of an ogee-modified delta-wing F5D-l airplane (exhibiting aerodynamics and longitudinal stability comparable to the SST) and of a subsonic jet transport (SJT) were used for evaluating the simulator and as reference configurations. Concurrent flight testing of the actual F5D-l airplane provided a good basis for comparison.

The dynamic response of the SST to seven different ground-effect models during controls-fixed and constant-attitude descents is presented. The response showed that the significant lift due to ground effect of the large delta airplane offers considerable potential for simplifying the landing flare, for either the manual or automatic landing task, if proper pitch stabilization is provided and the adverse lift due to control deflection can be eliminated. Results indicate that descent rate reductions of nearly 100 percent may be feasible without a flare maneuver (by maintaining constant pitch attitude).

The pilots' evaluations of each ground effect model showed that qualitative assessments are strongly influenced by the column force required to flare and by the occurrence of a noticeable nose-down trim change prior to the normal initiation of the flare maneuver. Pilot objections to the ground-effect trim change were alleviated by higher landing speeds, shallower approach angles, and pilot anticipation of the trim change.

Pilots found controllability near the ground less precise with the unaugmented SST than with the subsonic jet transport, mainly because of the reduced attitude stability and adverse lift due to elevator deflection (L_{δ_e}) of the tailless delta SST. The adverse L_{δ_e} delayed flight-path response, negated a significant portion of the ground-effect lift in trimming out the ground-effect pitching moment, and because of the pilot's location well ahead of the wheels, made judging the wheel height and sink rate difficult. The SST without control augmentation was, however, considered acceptable for emergency operation.

A summary of ground effects on delta-like wings is included in the appendixes.

INTRODUCTION

Early piloted simulator tests indicated piloting difficulties in landing the unaugmented delta-wing supersonic transport (SST). Although this early work (ref. 1) was primarily concerned with takeoff, in a preliminary evaluation of an unaugmented landing the pilots found control of the flare imprecise, landing performance inconsistent, and touchdown sink rates significantly greater than for a simulated subsonic jet transport. There are several possible reasons for poor control of the flare: (a) adverse lift with elevator deflection, (b) large pitching moment of inertia and small static margin, resulting in a low short-period natural frequency, (c) location of the pilot far from the center of gravity, (d) high control forces and improper control sensitivity (gearing), and (e) trim changes in ground effect.

In the simulator tests, the nose-down pitching moment due to ground effect appeared to be the primary source of the difficulty. However, flight experience with other delta aircraft had indicated that ground effect, when noticeable, behaved as a ground cushion during landing because of the favorable lift changes which apparently compensated for the unfavorable pitching-moment changes. For example, reference 2 discusses the flight characteristics of the HP 115, a slender delta research aircraft with an aspect ratio of 1 and a 20-foot wing span. Wind-tunnel and simulator studies indicated the HP 115 would have a nose-down pitching moment in ground effect; this caused concern about landing, but flight experience showed the aircraft to be comfortable to fly, effecting a marked ground cushion at low wheel heights.

Therefore, to evaluate SST flare characteristics, it appeared necessary to resolve questions regarding the validity or accuracy of the ground-effect data used in programming the simulator and the adequacy of the simulator for evaluating the landing maneuver. To answer these questions and investigate further the sensitivity of the aircraft response and handling characteristics to variations in ground effect, a program comprised of computer and piloted-simulator runs, wind-tunnel tests, and flight tests was initiated.

To verify the accuracy of the ground-effect data used in programming the simulator three tasks were performed: (1) available ground-effect data for delta-planform wings, based primarily on wind-tunnel tests, were analyzed; (2) flight and full-scale wind-tunnel tests were conducted to document the ground effect on a Douglas F5D-1 airplane with a modified ogee wing (hereafter called the F5D-1); and (3) a flight investigation was conducted to document the ground effect on a Convair 990 swept-wing transport. In order to check the adequacy of the simulator for evaluating the landing maneuver, two airplanes familiar to the pilots were represented on the simulator, the F5D-1 and a typical swept wing subsonic jet transport (hereafter referred to as the SJT). These configurations were then used for reference during comparative piloted simulator evaluations of the SST landing flare characteristics. The sensitivity of these flare characteristics to variations in the ground-effect model was determined by computer studies of airplane response for a matrix of ground effects, and the matrix was then assessed by pilots in the simulator.

The primary intent of this report is to discuss the results of the computer and piloted simulator investigations showing the manner in which ground effect influences the landing flare, and the factors that influence pilot acceptance. Validity of the SST ground effect and adequacy of the simulator are discussed in appendixes A and B, respectively.

Although supersonic transports will likely be equipped with stability augmentation, this study deals entirely with an unaugmented configuration in order to demonstrate the requirements for such augmentation, and to show the handling characteristics in the event of augmentation failure.

TESTS AND EVALUATIONS

The simulation portion of this study consisted of preliminary simulator validation runs plus two main study phases. In the first phase, SST flare characteristics were evaluated using a ground-effect model based on double-delta SST wind-tunnel measurements, and compared with SJT and F5D-1 characteristics. In the second phase, the sensitivity of SST flare characteristics to variations in the ground-effect model was determined from computer studies of airplane response and piloted simulator runs.

Simulator Validation

Simulations of aircraft familiar to the pilots (the F5D-1 and the SJT) were used as a means for judging the simulator's capabilities and as reference configurations for evaluating the SST flare characteristics. Judgment of the simulator adequacy was based largely on the pilots' subjective assessments during the initial series of evaluation landings in the simulator. To have a good basis for comparison, the pilots, on several occasions, flew the actual and the simulated F5D-1 on the same day. Their assessments of simulator adequacy are discussed in appendix B.

Comparative Evaluation of SST Flare Characteristics

The comparative evaluation of the SST flare characteristics was based on 64 SST and 76 reference airplane landings at various speeds by three Ames research pilots. See table 1. Each session in the simulator consisted of approximately 9-12 data runs, in addition to as many familiarization runs as were considered necessary by the pilot at the beginning of each session. The task consisted of a visual landing of the simulated aircraft following breakout to visual flight at 200-feet altitude from a 6-mile ILS 3° approach.

TABLE 1.– DISTRIBUTION OF TEST RUNS

Configuration	SST			F5D-1	SJT		
Approach speed, knots	120	135	150	140	131	146	161
Pilot A	5	6	6	—	3	3	3
B	6	12	8	14	6	9	6
C	6	9	6	14	6	6	6
Totals	17	27	20	28	15	18	15

Variations of SST Ground-Effect Model

In order to define the effects of variation in ground effect, seven ground-effect models were studied using nonpiloted and piloted SST simulator runs. Parameters varied were the magnitude of the incremental lift, magnitude of the incremental pitching moment, and the ground effect encounter height. A series of nonpiloted analog runs was made consisting of entries into ground effect at varying descent angles (1° to 3°) (1) with the controls fixed, and (2) with pitch attitude maintained constant. Two pilots (A and B) flew a series of evaluation landings with each of the ground-effect models, starting from 2 miles out on a 3° approach and with landing speeds varying from 120 to 160 knots. Pilot comments and pilot opinion rating numbers were recorded. Pilots used the Cooper pilot opinion rating scale, shown in table 2 and described in reference 3.

TABLE 2.– COOPER PILOT–OPINION RATING SCALE

Operation	Rating: Adjective	Rating: Numerical	Description	Primary mission accomplished	Can be landed
Normal	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
None	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable – dangerous	No	No
		9	Unacceptable – uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1] Failure of a stability augmenter.

TEST EQUIPMENT

The simulator had a transport-type fixed cockpit equipped with basic flight-test instruments. An external visual scene was provided by means of a projected black and white closed-circuit television picture (unity magnification). The picture was generated by a servo-driven television camera moving over a 1:1200-scale landscape model. Figure 1 shows the model and television camera. Figure 2 shows a view of the runway and the instrument panel during a landing flare. The runway was 200 feet wide and 10,000 feet long.

The pilot's station was equipped so that the flight controls could be changed for the various configurations. For the SJT and the SST, the pilot was provided four transport-type thrust levers on a right-hand quadrant and a y-shaped control wheel (designed primarily for improved instrument

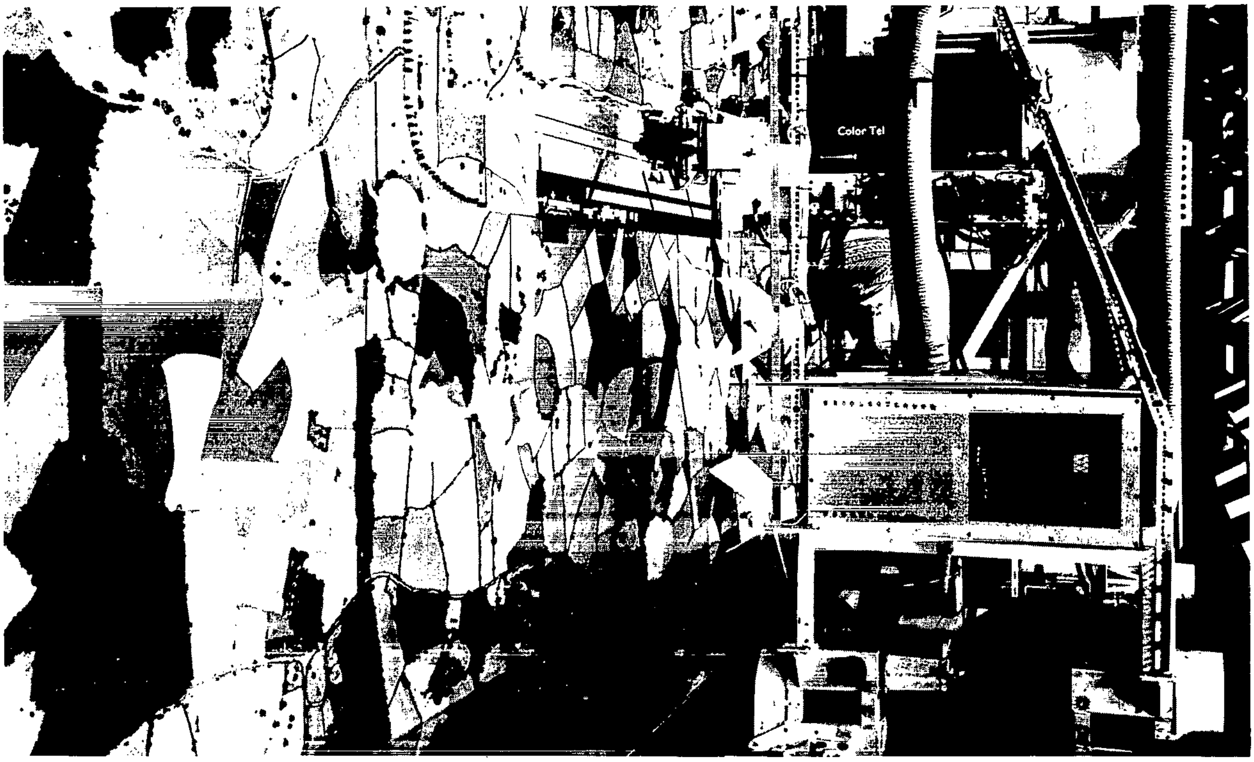


Figure 1.– Television camera system with model landscape and runway.

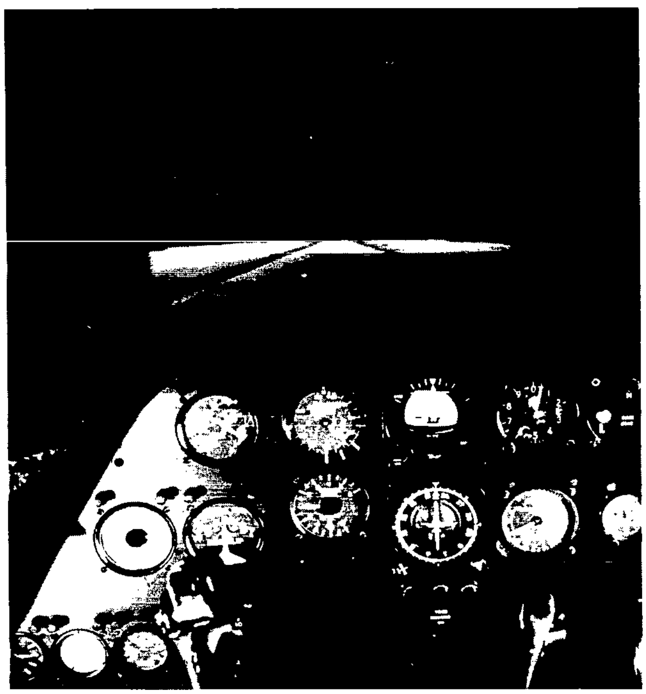
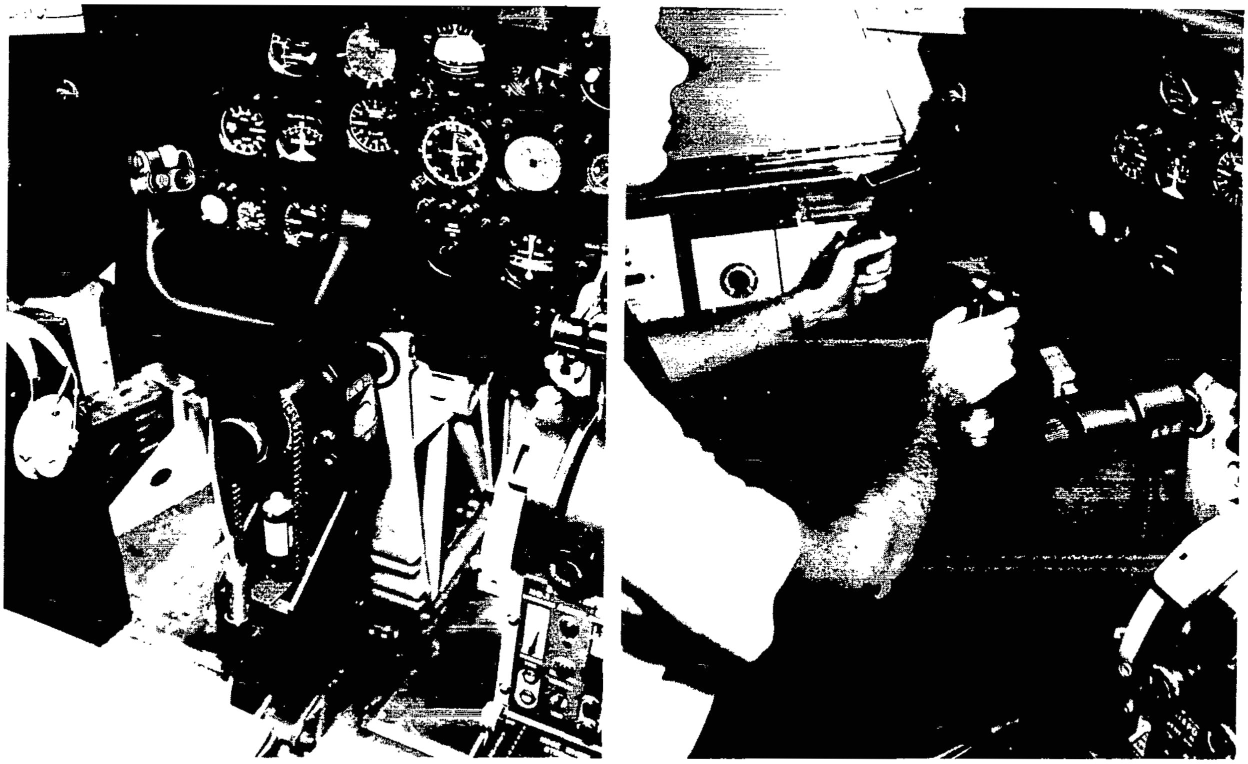


Figure 2.– View of the simulator instrument panel and external visual scene from over the pilot's shoulder.



(a) Y-shaped control wheel and right-hand thrust-lever quadrant used for SST and SJT simulations.

(b) Control stick and left-hand thrust lever for F5D-1 simulation.

Figure 3.- The two control arrangements used in the study.

	SST	F5D-1	SJT
Column breakout force, lb	2	4.5	2
Column force gradient, lb/in.	9	4.25	9
Elevator gearing, deg/in.	See below	2.9	2.2
Elevator travel limits, deg	10.5/-25	11/-30	11.5/-22
Elevator rate limits, deg/sec	±25	±25	±25

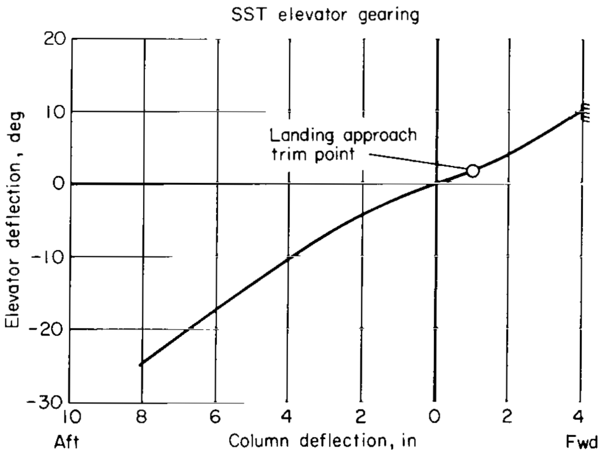


Figure 4.– Comparison of longitudinal control system characteristics.

visibility) as shown in figure 3(a). Comments regarding this control wheel are given in reference 1. For the ogee F5D-1, a single left-hand thrust lever and a control stick were provided the pilot (fig. 3(b)). Control force characteristics were provided by spring and damper systems. Figure 4 illustrates the longitudinal control system characteristics used for the various configurations. SST control system characteristics were representative of SST design values at the time of the study. Note that the SST configuration utilized a nonlinear elevator gearing.

Two general purpose electronic analog computers were programmed to represent the rigid body motion of the airplanes in six degrees of freedom. All computations assumed sea-level standard conditions with smooth air. Reference 4 gives additional details about the simulation, including a complete description of the equations of motion. The computer representation of the ground plane influence on aerodynamic lift, drag, pitching moment, and elevator effectiveness is discussed in the section entitled "Description of Ground-Effect Models."

TEST CONFIGURATIONS

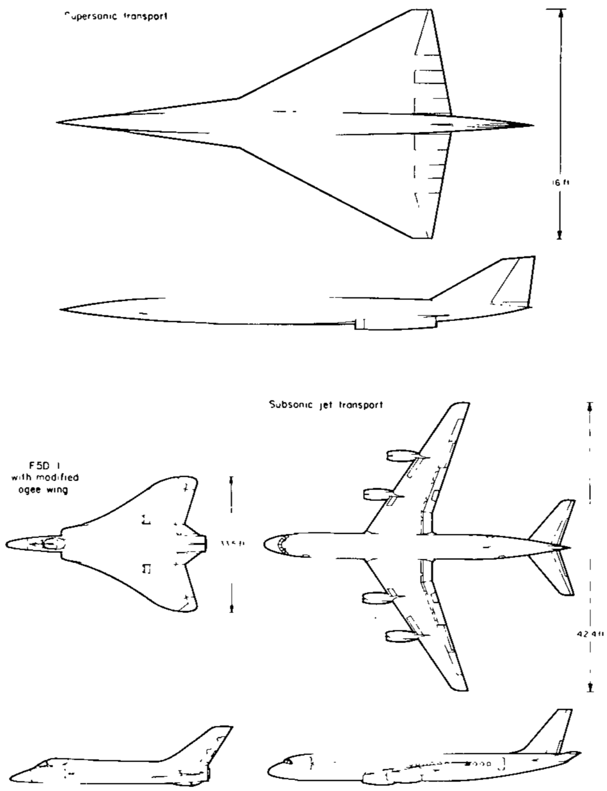


Figure 5.– Two-view sketches of the three simulated airplane configurations.

The configurations of the three simulated airplanes are shown in figure 5. Table 3 lists significant aerodynamic and dimensional parameters. The F5D-1, described in references 5 and 6, was somewhat similar to the SST in wing planform (aspect ratio), wing loading, speed-thrust stability [(dT/W)/dV] and static longitudinal stability ($C_{m_{C_L}}$). The SJT simulation more nearly resembled the SST in gross weight and wing span, and provided a basis for comparing SST handling characteristics with those of current jet transport aircraft.

Elevons provided the longitudinal control for the F5D-1 and the SST. No flaps or other high-lift devices were used for these two airplanes. The SJT had conventional control surfaces and the flaps were maintained at the normal approach setting.

The "free air" lift, drag, and pitching-moment characteristics for the three simulated aircraft are shown in figure 6. Note the similarities between the characteristics of the two delta airplanes in comparison with those of the

TABLE 3.– COMPARISON OF SIGNIFICANT DESCRIBING PARAMETERS AT THE NOMINAL APPROACH SPEED FOR THE THREE TEST CONFIGURATIONS

	SST	F5D-1	SJT
Gross weight, lb	270,000	23,000	200,000
Wing loading, W/S, lb/ft^2	33.4	34.8	72.5
Mean aerodynamic chord, ft	86.8	22.6	22.16
Aspect ratio	1.66	1.70	7.36
Pitch inertia, slug-ft^2	18.6×10^6	83.5×10^3	3.9×10^6
Nominal approach speed, knot	135	140	146
Static margin, $-C_{m_{C_L}}$	0.023	-0.017	0.20
M_{δ_e}, 1/sec^2	-0.85	-4.11	-1.04
L_{δ_e}, 1/sec	0.243	0.216	0.039
ω_{nsp}, rad/sec	0.72	0.77	1.25
ζ_{sp}, 1/sec	0.98	0.78	0.62
d(T/W)/dV, 1/knot	-0.0016	-0.0015	0.0001

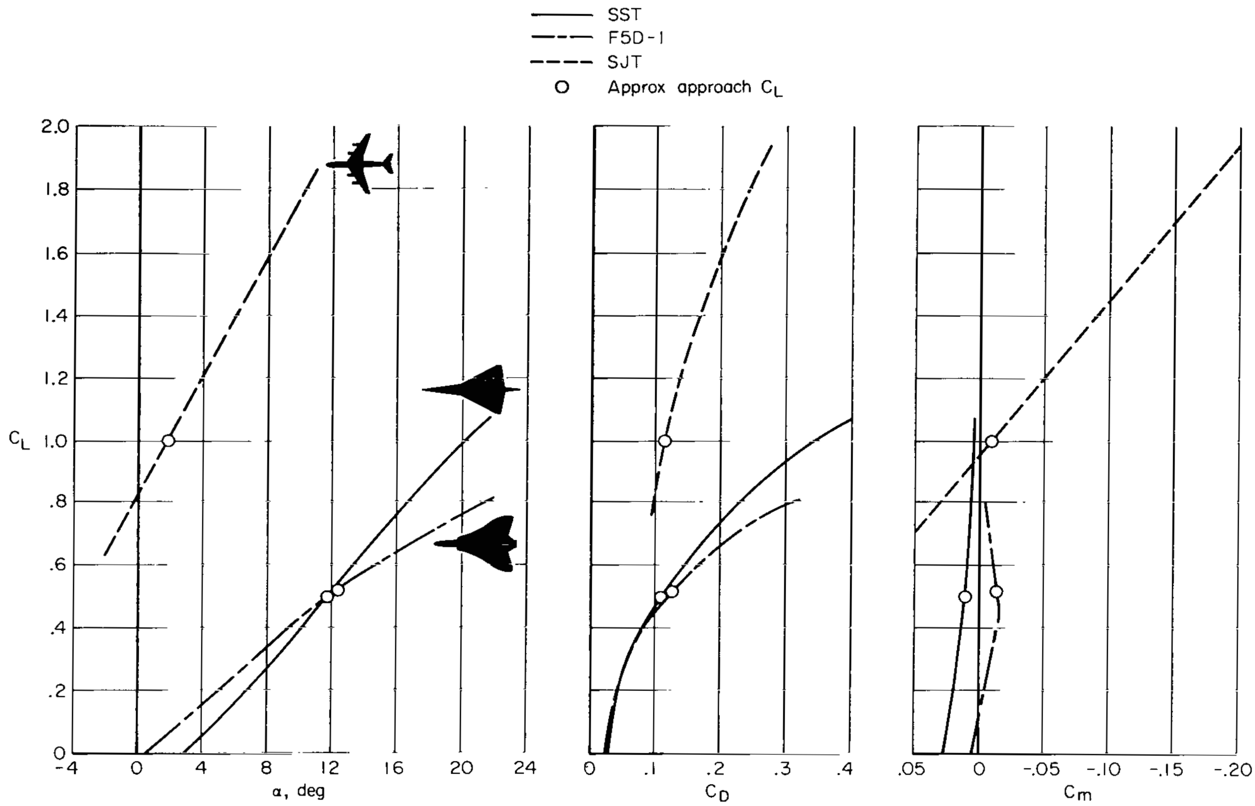


Figure 6.– Basic lift, drag, and pitching-moment characteristics as simulated for the three airplanes. Out-of-ground effect, landing gear extended.

swept wing SJT. The absence of high-lift devices and the low lift-curve slopes of the SST and F5D-1 result in an approach C_L about one-half that for the SJT, and require a much greater angle of attack. Note also the near-neutral static longitudinal stability $C_{m_{C_L}}$ exhibited by the two delta airplanes. The ground-effect representations are described in the following section.

The pitch-axis drive signal to the visual scene was biased 6° nose-down for the SST and F5D-1 to represent a flight deck inclined for improved visibility.

DESCRIPTION OF GROUND-EFFECT MODELS

In general, ground effect on an airplane is characterized primarily by an increase in lift, a nose-down pitching moment, a drag reduction (at constant C_L), and an increase in control effectiveness. The combined effect on the landing task depends on the magnitude and phasing of the relative contributions, which vary considerably with airplane configuration, and on the basic airplane's handling characteristics. The following discussion will describe the form used to represent the ground effect, compare the basic ground-effect models for the three airplanes in this study, describe the alternate SST ground-effect models studied, and indicate the data sources used for the individual aircraft ground-effect models.

Form of Representation

Examination of a considerable quantity of ground-effect data indicated that the effects on lift and pitching moment can be represented as the ratio of the incremental change in lift (or pitching moment) coefficient, for a given α, to the "free air" lift coefficient,

$$\frac{(\Delta C_L)_{GE}}{C_{L_\infty}} \quad \text{and} \quad \frac{(\Delta C_m)_{GE}}{C_{L_\infty}}$$

This ratio tends to remain relatively constant for the α-range representative of the approach and landing.[1] Ground effect on drag was programmed in the form $(\Delta C_D)_{GE}/(C_D\text{-}C_{D_0})_\infty$, which makes the drag change approximately proportional to the free-air induced drag for a given α. The same height-factor curve was used for both the lift change and the drag change. Figure 7 shows the ground-effect analog diagram based on this form of representation.

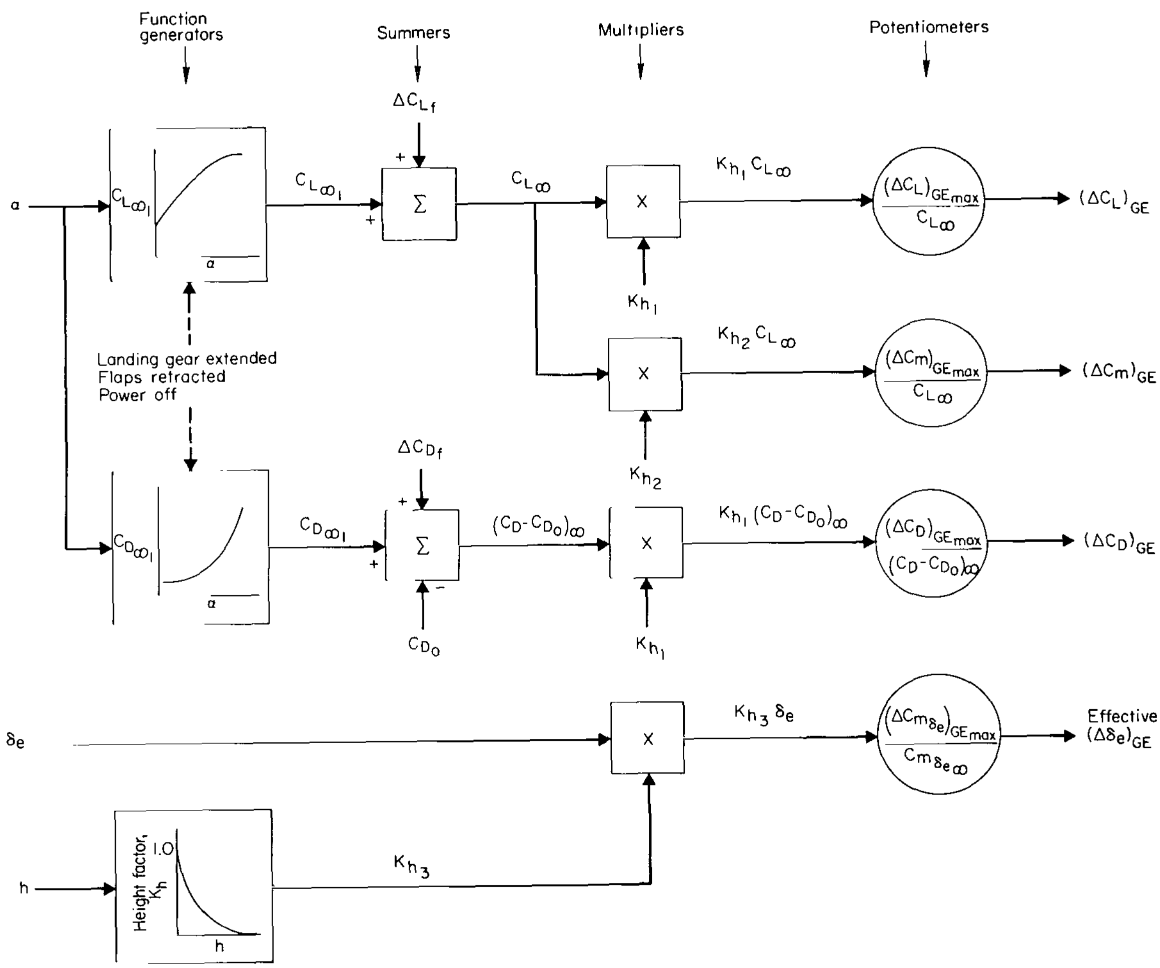


Figure 7.– Diagram of ground-effect analog representation used in the simulator study.

[1] The validity of this representation decreases for swept-wing configurations at angles of attack exceeding about 8°. There is evidence that at higher angles of attack the incremental lift due to ground effect for such configurations decreases, and even becomes negative in some cases.

Comparison of Basic Ground-Effect Models

The simulated ground effect on lift and pitching-moment coefficients for the three subject airplanes is compared in figure 8, with ground-effect model 1 shown for the SST. This figure shows an increase in lift coefficient due to ground effect of about 60 percent for the SST as compared with 30 percent and approximately 10 percent for the F5D-1 and SJT, respectively. The change in pitching-moment coefficient with ground effect for the SST and the SJT is about the same at constant α, while that for the F5D-1 is about one-third the value for the two larger aircraft. The encounter height depends on airplane size; quarter-chord ($0.25\,\bar{c}$) heights at ground-effect encounter were equal to 70-85 percent of the wing span for the three airplanes in this study. This corresponded to wheel heights of about 80 feet for the two larger airplanes and 22 feet for the F5D-1. Values for the drag ratio described above (at constant α) were +0.60, +0.36, and -0.30 for the SST, F5D-1, and SJT, respectively, and all resulted in a drag decrease at constant C_L.

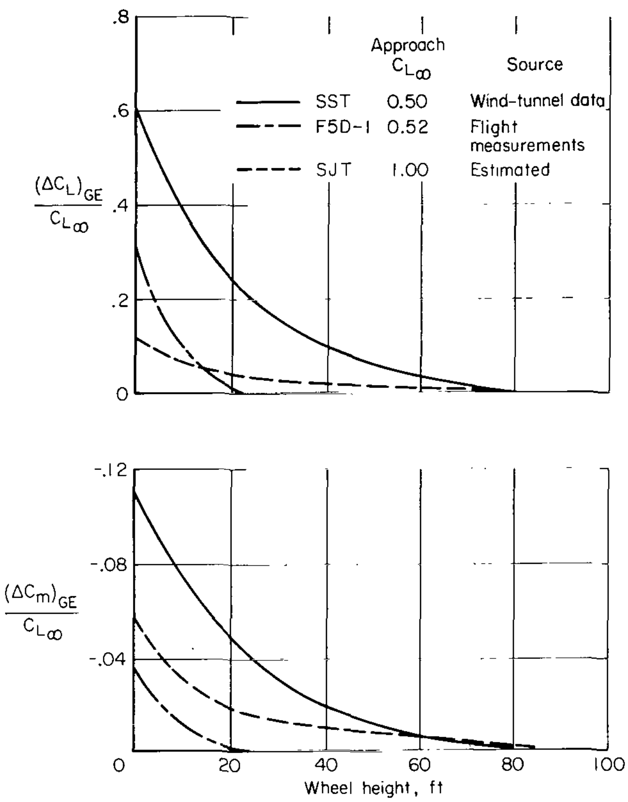


Figure 8.– Ground effect on lift and pitching-moment coefficients as simulated for the three airplanes. GE model 1 is shown for the SST.

Data Sources

SST ground-effect model 1 was based on unpublished wind-tunnel data. These data were generally substantiated by the data search discussed in appendix A.

F5D-1 ground effects on lift and pitching moment were based on flight measurements reported in reference 6. These results are also discussed in appendix A. Ground effect on drag was based on wind-tunnel measurements reported in reference 7. Elevator effectiveness was unchanged by ground effect for the simulated F5D-1.

The SJT ground-effect model was based on estimates. More reliable SJT data have become available since these tests, and some of these data are compared with the modeled ground effect in figure 9. The open test points were obtained at Ames with the Convair 990A airplane shown in figure 10. Pilots report that this airplane effects a significant "ground cushion," and is probably near the upper boundary of ground effects for current swept-wing transport aircraft. The shaded points of figure 9 were obtained from moving-belt ground-plane wind-tunnel tests on a 0.068 scale model similar to the Boeing 367-80 (707 prototype) airplane (ref. 8). Although equipped for flap blowing for boundary-layer control, the data used for the comparison in figure 9 are without blowing.

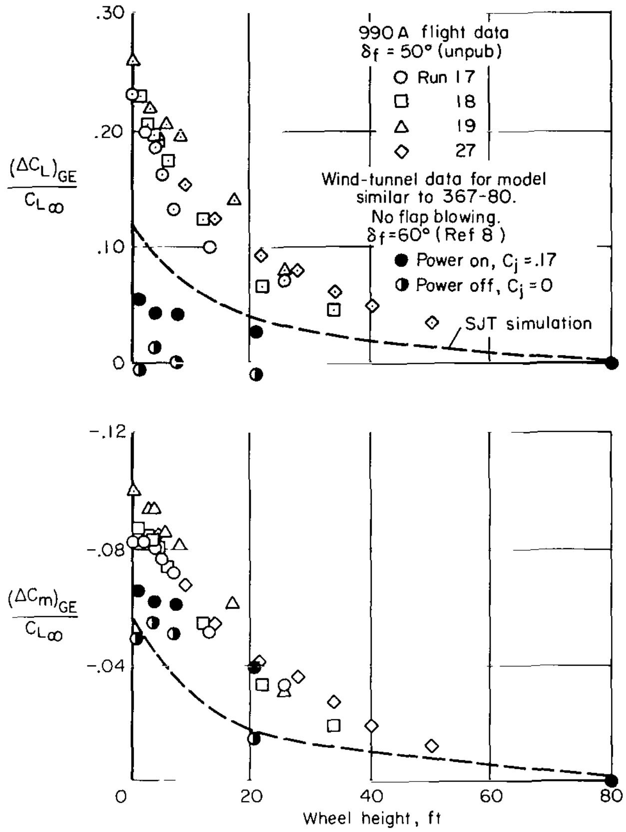


Figure 9.– Comparison of SJT ground-effect model with Convair 990A flight-test results and with wind-tunnel measurements on an SJT model. C_{L_∞} approximately 1.0 for all data shown.

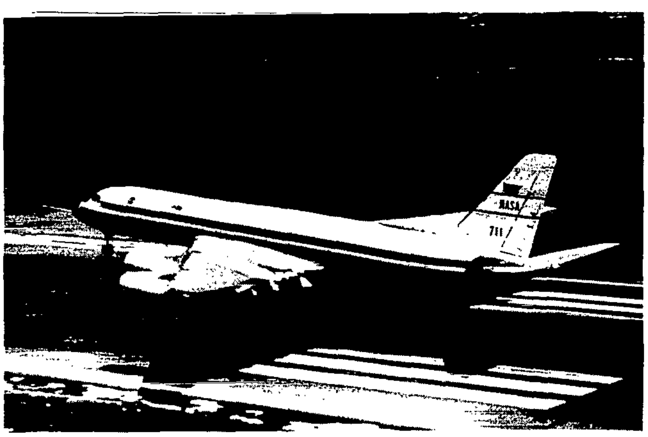


Figure 10.– Convair 990A subsonic jet transport.

The differences in the lift data shown from these two sources may be due to the different flap designs and slightly different wing planforms represented. On the basis of these data, it is felt that the ground-effect lift used in this study represented a reasonable mean for this type of airplane. The simulated ground-effect pitching moment appears slightly less in magnitude than the most representative value but, in combination with the simulated ground-effect lift, is considered within the envelope of ground effects for subsonic jet transports.

Alternate SST Ground-Effect Models

In addition to ground effect model 1, six alternate SST ground-effect models were evaluated. Table 4 lists the basic characteristics of each of the seven models; the variation with height is presented in the discussion of the computed response studies. Model 3 was identical to model 1 with the exception that the pitching-moment change was reduced by one-half. Model 2 represented another set of wind-tunnel measurements on the subject double-delta planform, but these data were later discounted because of wind-tunnel model support interference effects. The evaluations of this ground-effect model are included because of the interesting and useful information yielded. The ground-effect lift of model 2 was only about half that of model 1, but this reduction was partially offset because the ground-effect lift was encountered 5-10 feet higher than the pitching moment. Models 4 and 5 are variations of 2, with reduced ground-effect pitching moments. Model 4 is considered nearest ground effect measurements from XB-70 airplane tests, discussed in appendix A. Models 6 and 7 were included to indicate the effect of reduced airplane size, with ground effect confined to 16-18 feet above ground; model 7 approximates the ground effect for the F5D-1.

TABLE 4.– SST GROUND–EFFECT MODELS

Model	Value at main gear touchdown				Initiation height, ft		
	$\frac{(\Delta C_L)_{GE}}{C_{L_\infty}}$	$\frac{(\Delta C_m)_{GE}}{C_{L_\infty}}$	$\frac{(\Delta C_{m_{\delta_e}})_{GE}}{C_{m_{\delta_{e_\infty}}}}$, $\frac{(\Delta C_{L_{\delta_e}})_{GE}}{C_{L_{\delta_{e_\infty}}}}$	$\frac{(\Delta C_D)_{GE}}{(C_D-C_{D_o})_\infty}$	$\Delta C_L, \Delta C_D$	ΔC_m	$\Delta C_{m_{\delta_e}}$
1	0.6	-0.11	0.32	0.60	76	76	76
3	↓	-.055	↓	↓	↓	↓	↓
2	.32	-.09	.18	.20	70	64	21
4	↓	-.045	↓	↓	↓	↓	↓
5	↓	-.030	↓	↓	↓	↓	↓
6	↓	-.020	.04	↓	18	16	3
7	↓	-.060	↓	↓	↓	↓	↓

RESULTS AND DISCUSSION

Comparison of SST, F5D-1, and SJT Landing Characteristics

Landing characteristics of the SST (programmed with ground-effect model 1) and comparisons with the F5D-1 and SJT are discussed in the following five subsections: general longitudinal characteristics, flare characteristics, effect of elevator control on lift (L_{δ_e}), effect of varying landing speed, and landing performance. The pertinent results are summarized in table 5.

TABLE 5.– SUMMARY OF SST COMPARISON WITH F5D–1 AND SJT

Category	Factors	SST (unaugmented, GE 1)	F5D-1 (ogee)	SJT
Nominal approach speed, knots	-	135	140	146 (1.41 V_s)
General longitudinal characteristics (ILS tracking task)	Pilot rating	Unsatisfactory 4 - 5-1/2	Unsatisfactory 4 - 4-1/2	Satisfactory 1-1/2 - 3-1/2
	Comment	Pitch attitude wanders	Pitch attitude wanders	Pitch attitude well-behaved
Flare characteristics	Pilot rating	Unsatisfactory 3-1/2 - 6-1/2	Good 1 - 2	Satisfactory 2 - 4
	Comment	Objectionable nose-down pitching moment; difficult to control descent rate	Ground effect barely detectable; easy to land	Requires positive flare; descent rate easy to control
Effect of L_{δ_e}	Flight path response	Sluggish	Good, due to high control sensitivity	Good
Effect of increasing the landing speed by 15 knots (flare task)	Change in pilot rating	-3/4 (improvement)	-	No change
	Change in touchdown vertical velocity	No change in average, reduced deviation	-	1 ft/sec increase
Landing performance	Touchdown vertical velocity, probability of exceeding 5 ft/sec	53 percent	15 percent	6 percent
	Touchdown position, mean and standard deviation	2240 ±880 ft	2600 ±1020 ft	2670 ±970 ft

Typical simulator time histories of SST and SJT landings are compared in figure 11. These clearly show the pitch attitude wandering characteristic of the SST, as well as the associated difficulties in stabilizing rate of descent. Rate of descent is continually in oscillation, and the realization of a low touchdown vertical velocity depends upon when landing impact occurs with respect to the oscillation. In comparison, the SJT traces of pitch attitude and descent rate are well-behaved and a controlled flare maneuver is readily identified.

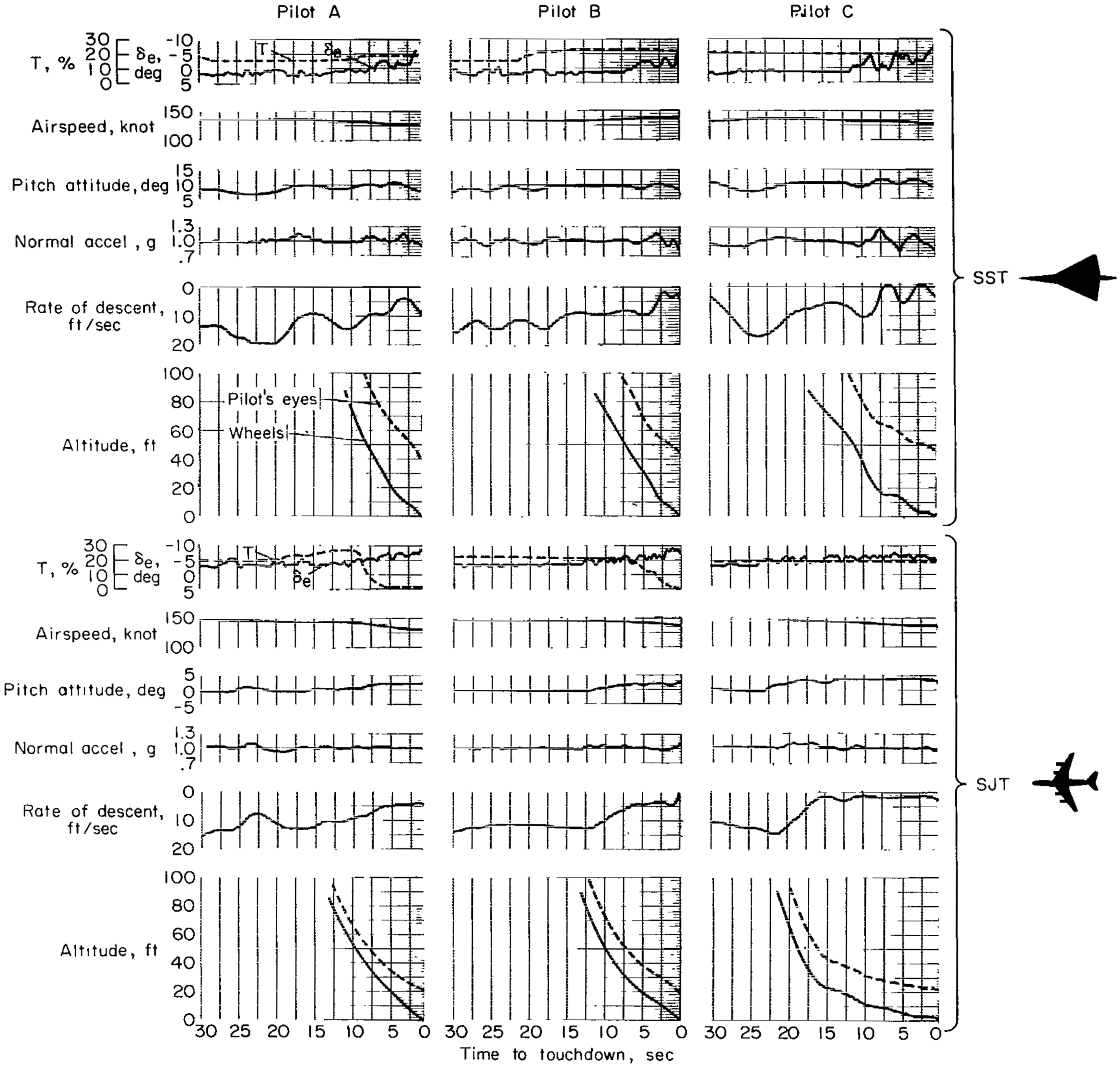


Figure 11.- Comparison of simulator landing time histories. SST: V_a = 135 knots, GE model 1; SJT: V_a = 146 knots.

General longitudinal characteristics– Because the pitch dynamics of the basic airplane can contribute to control difficulties during the flare, it is pertinent to first describe the longitudinal characteristics exclusive of ground effect. During the program, pilots evaluated the attitude stability, longitudinal (attitude) response, and flight path control, primarily on the basis of the ILS tracking task in smooth air. On this basis, they judged the longitudinal characteristics of the unaugmented SST as unsatisfactory, but acceptable for emergency operation. Pilot ratings ranged from 4 to 5-1/2, with primary concern related to the attention required to minimize pitch attitude wandering and difficulty in establishing and maintaining a desired rate of descent, as evidenced by the landing time histories shown in figure 11. For comparison, pilot ratings for the SJT were satisfactory, ranging from 1.5 to 3.5. F5D-1 pilot ratings were 4 to 4.5, with complaints generally based on pitch-attitude wandering, a characteristic which appeared identical in the simulator and in flight.

Because of the low natural frequency of the SST's short-period mode, a control input caused a long-period pitch response that required a significant reverse control input to arrest. Pilots found it difficult to locate a trim position; and when disturbed from trim, the pitch rate would not decay before a pitch correction was required. Thus in pitch it was necessary to fly the airplane continually and it was difficult to avoid overcontrolling.

Flare characteristics– Flare characteristics for the SJT received pilot ratings of 2-4, or generally satisfactory but with some mildly unpleasant characteristics. A positive effort was required to flare the airplane and hold the nose up until touchdown; however, the reduction in descent rate was easy to control. Pilots considered the F5D-1 easy to land and the ground effect difficult to detect, and assigned a pilot rating of 1-2 (excellent to good).

All evaluating pilots rated the SST's flare characteristics with ground-effect model 1 between the 3-1/2 and 6-1/2 boundaries, or unsatisfactory. Pilots B and C found the SST ground effect objectionable in that the nose-down moment was noticeable before their normal flare initiation and required considerable aft column displacement and force to compensate for it. They found it very difficult to control attitude and descent rate accurately close to the ground. Pilot A, who tended to initiate flare at a greater altitude than B and C and before encountering ground effect, found it not significantly objectionable. However, he rated it unsatisfactory on the basis that when the flare was delayed, too much force was required and airplane response was insufficient to allow adequate recovery, a situation comparable to that objected to by pilots B and C. More detailed pilots' comments are given in appendix C.

Because of the strong influence the ground effect appears to exert on pilot opinion and the somewhat uncertain nature of ground-effect data, six variations of the ground-effect model were also evaluated. The results are discussed later in the report.

Because of the SST pilot's location well forward of the wheels, pitch attitude and pitch rate can significantly influence his judgment of wheel height and vertical velocity. The difference between the sink rate at the SST wheels and at the pilot's eye level is evident in the slopes of the SST altitude traces in figure 11. Note that a change in sink rate perceived visually by the pilot does not occur at the wheels until approximately 2 seconds later (450-500 ft farther down the runway).

All pilots found that the best thrust-management technique with the SST was to leave thrust on during the flare maneuver, as is common practice for most low-aspect-ratio aircraft. (See fig. 11.) Varying techniques were used with the SJT. Pilot A abruptly cut thrust at a wheel height of about 50 feet on all runs, pilot B gradually reduced thrust during the final 30 feet, and pilot C used thrust for the flare on several runs and used the gradual reduction technique on others. Reference 9 identifies and discusses the requirement for varying thrust management techniques during the landing flare.

Effect of L_{δ_e}– The pilots noted that SST elevator effectiveness appeared low and flight-path-angle response was sluggish. Pilot A stated "Sluggish response is objectionable during flare when rapid last-second flight-path corrections are required. These can occur as a result of pilot technique, misjudgment, or turbulence. Occasional hard landings and/or delayed touchdowns will surely result. The sluggish response is difficult to identify as a problem during the approach phase, however."

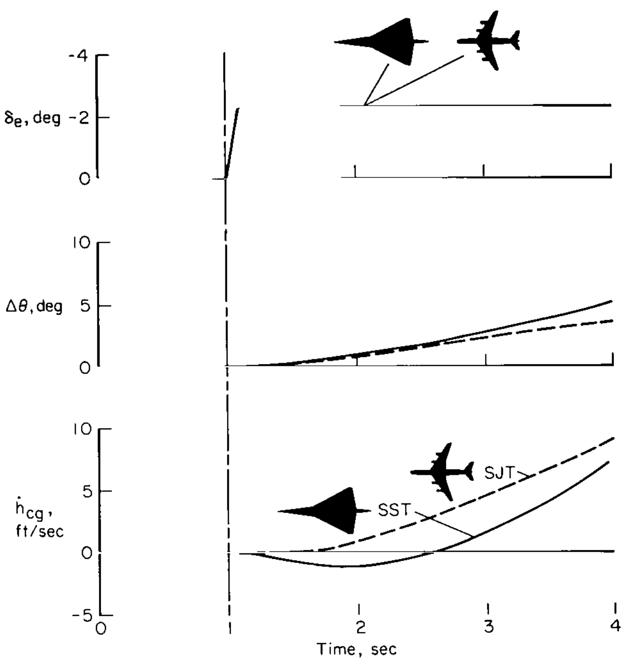


Figure 12.– Response to pitch control step input showing lag effect of adverse lift with elevator deflection.

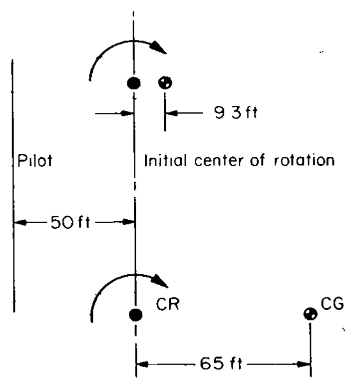


Figure 13.– Sketches showing initial center of rotation following a pitch control input.

Response to a column step input is shown in figure 12. Although initial pitch attitude response is comparable to the SJT, rate of descent (flight path) response lags the input by over 1-1/2 seconds. This lag is due to L_{δ_e}, the loss in lift caused by the control surface deflection, and results in an initial adverse flight-path response until the aircraft has rotated sufficiently to compensate for the lift loss.

Another way to show the effect of the L_{δ_e} is to examine its influence on the aircraft center of rotation as illustrated in figure 13. Note that for both airplanes the initial center of rotation following a control input is approximately 50 feet behind the pilot. However, the CG (and also the landing gear) of the SST is 65 feet aft of the initial center of rotation as compared to 9 to 10 feet for the SJT. This means that the initial height, height rate, and normal acceleration responses at the SST pilot's station appear little different from the SJT, but the response at the CG (or wheels) is far different. In fact, in responding to a pitch control input, the wheels are initially translating in the opposite direction and at a greater rate than that sensed by the pilot.

SST ride qualities reflect the effects of L_{δ_e} and poor stability. Comparison of the normal acceleration (at the CG station) traces in figure 11 shows that SJT variations seldom exceeded +0.1 g and rarely were negative. SST incremental accelerations reached +0.25 g and often, when abrupt control inputs were used, negative values resulted from the L_{δ_e} effect. Passengers would find such a ride uncomfortable, but not unreasonable for an emergency condition.

Effect of varying the landing speed– Increasing the landing speed improved controllability of the SST, due to increased static stability and control sensitivity (aircraft response), and decreased the magnitude of the ground effect ΔC_m due to the reduced C_L. A 15 knot increase in landing speed caused a 3/4 pilot-rating-unit improvement, as shown in figure 14. In comparison, varying the landing speed of the SJT ±15 knots (1.26 V_S to 1.55 V_S) did not change its pilot rating. Also shown in figure 14 are the mean touchdown vertical velocities and the standard deviation from the mean. Reducing approach speed reduced touchdown vertical velocity for the SJT, but did not improve the SST values. The difficulty reported in controlling SST flight path (or vertical velocity) near the ground is indicated by the greater deviation of the SST values compared with SJT values.

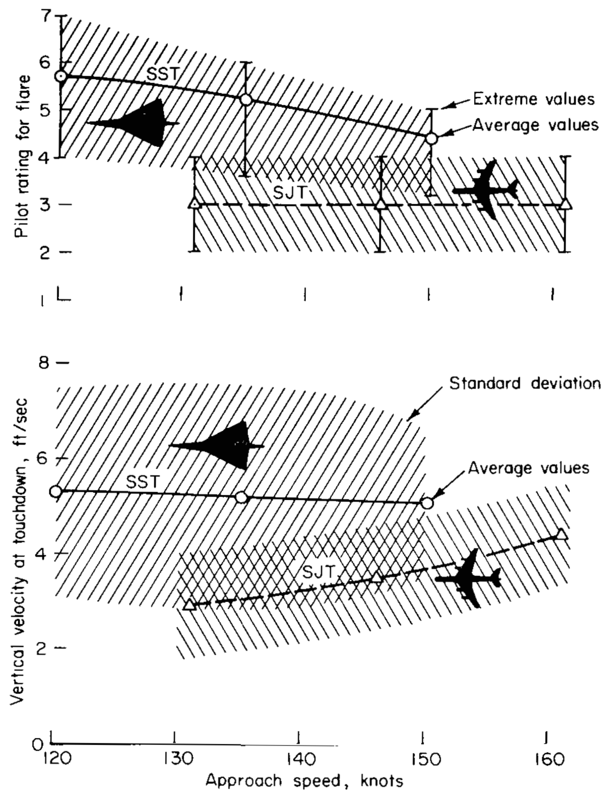
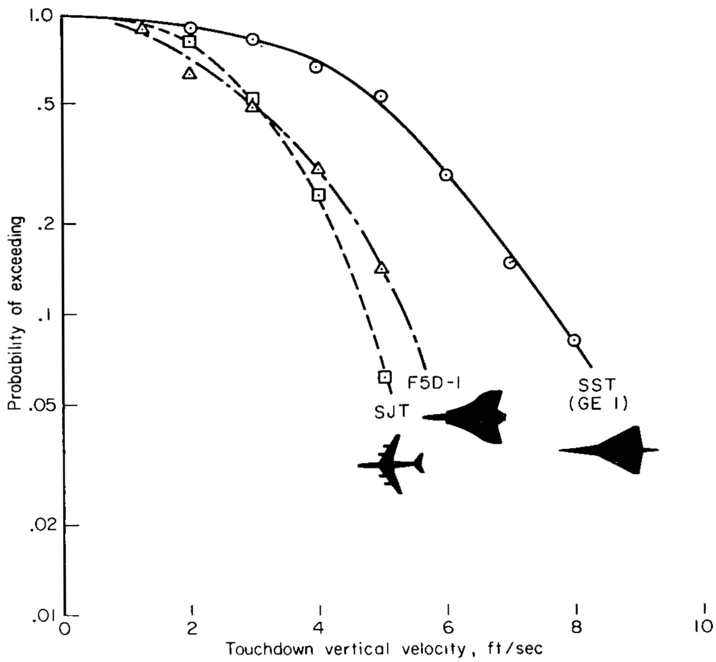


Figure 14.– Speed effect on SST and SJT flare characteristics and landing performance with corresponding pilot opinion ratings. (SST GE model 1)

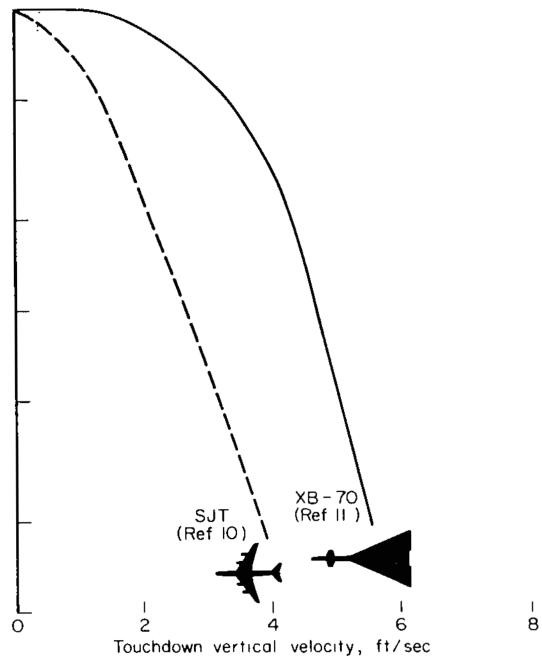
Landing performance comparison– Landing performance was measured in the form of touchdown vertical velocity and touchdown position along the runway. Throughout the test series, the pilots were not making a concentrated effort to minimize touchdown vertical velocity or runway distance, but were attempting to make realistic landings while subjectively evaluating the ground effect. Because all three airplanes (SST, F5D-1, and SJT) were flown on the same simulator with the same objectives, differences in performance are attributed primarily to airplane characteristics. However, comparisons of absolute simulator values to flight landing data should not be made because of the differing objectives and conditions between simulation and actual flight operations. Although the landings made in the simulator represent a small statistical sample, enough were made to confirm the difficulties reported by the pilots.

Figure 15(a) shows the probability of exceeding various values of touchdown vertical velocity for the three simulated airplanes. SST landings were significantly harder than the F5D-1 and SJT landings. There was 53 percent probability of exceeding 5 ft/sec (about one-half the nominal landing gear design limit) with the SST as compared to 15 percent for the F5D-1 and 6 percent for the SJT.

Figure 15(b) shows the same type of data from actual flight experience with an SJT and a large tailless delta, the XB-70. The SJT data are from reference 10 and are operational data recorded for a turbine-powered transport of the type simulated. The delta-wing data are from reference 11 and are based on 71 flight-test landings of the XB-70. These landings were made under near-ideal weather conditions, from shallow approach angles (1° to 2°) at relatively high final approach speeds (approximately 170 knots), and with pilots of chase aircraft often aiding the XB-70 pilot by calling out wheel height. Even with these advantages, the XB-70 exhibited higher touchdown vertical velocities than the SJT.



(a) Simulator results.



(b) Flight results.

Figure 15.– Probability of exceeding various vertical velocities at landing impact. Simulator and flight comparisons of SJT with delta-wing aircraft. Approach speeds for simulator data: SJT 131-146 knots, F5D-1 140 knots, SST 135-150 knots.

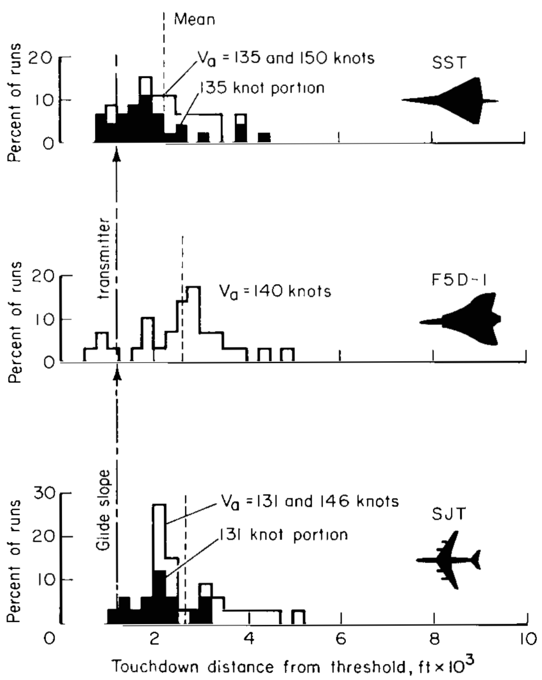


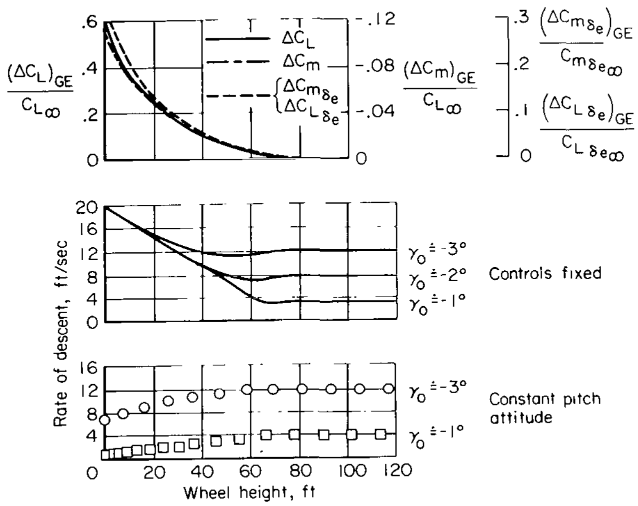
Figure 16.– Comparison of touchdown distance distributions for the three simulated airplanes.

Touchdown distance distributions for the three simulated airplanes are shown in figure 16. The effect of landing approach speed is illustrated for the SST and SJT. Note that the touchdown distances corresponding to the lower approach speeds generally group nearer the threshold. Also, the ranges of distribution correlate with the pilot evaluations and touchdown vertical velocities shown in figure 14. For the SST, 135-knot touchdown points ranged from 750 to 4500 feet, compared with 1000 to 4000 feet for the 150-knot approaches, indicating the improved flare characteristics reported for the higher speed. SJT landing performance was better at 131 knots (1.26 V_S) than at the higher landing speeds.

Computer Studies of SST Response to Various Ground-Effect Models

The SST simulator program was used in nonpiloted computer runs for each of the seven ground-effect models described in table 4 to investigate the sensitivity of the SST to ground-effect variations. These tests were conducted primarily because of speculation that the "ground cushion" of the delta planform would allow "no-flare landings." Whether this potential can be realized depends on the factors discussed here. For one thing, completely different conclusions were reached when "no-flare" was interpreted as constant attitude (provided by appropriate control inputs) instead of constant control position with attendant attitude changes.

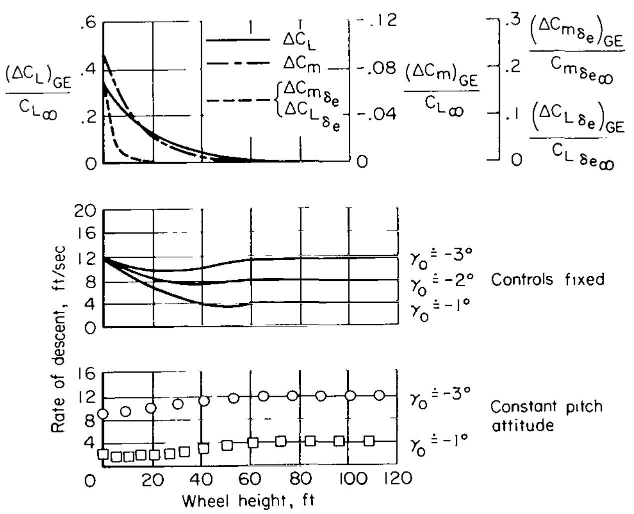
For these runs, the simulated airplane was released from an initial trimmed flight condition at 135 knots airspeed, 150 feet altitude, and a descending flight-path angle of 1°, 2°, or 3°. Two types of runs were conducted, (1) those in which the controls were assumed fixed at the initial free-air trim position and (2) those in which the elevator surfaces were deflected as required to maintain constant pitch attitude throughout the run.



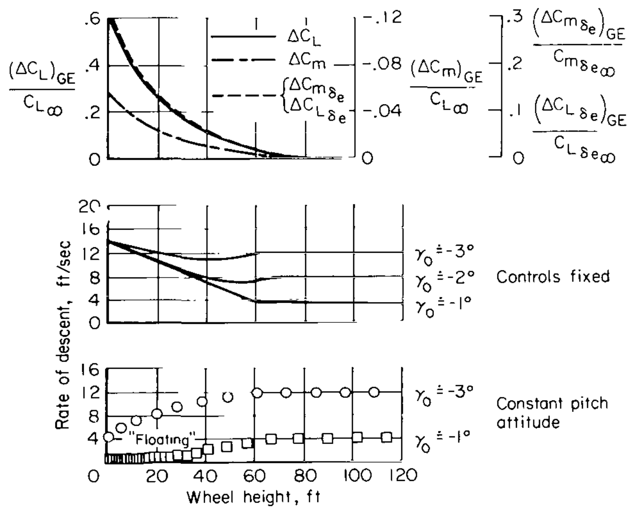
(a) Ground-effect model 1.

The results of these runs are shown in figures 17(a) – 17(g) with descent rate plotted versus wheel height. In order to demonstrate the floating effect that occurred in some of the constant attitude runs, these runs are shown as loci of points at 1-second intervals. For ease of interpretation, the ground-effect model is shown for each case, also plotted against wheel height. Several interesting observations can be made by comparing the various responses, as discussed in the following sections.

Effect of leaving controls fixed– Consider first the controls-fixed run for ground-effect model 1 (fig. 17(a)) in which lift increases 60 percent due to ground effect.

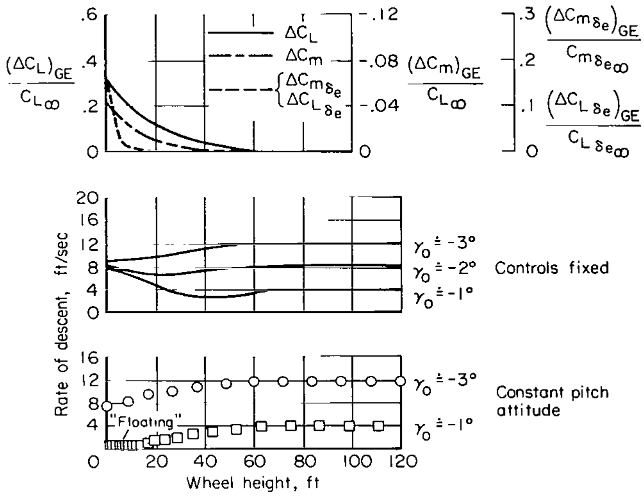


(b) Ground-effect model 2.

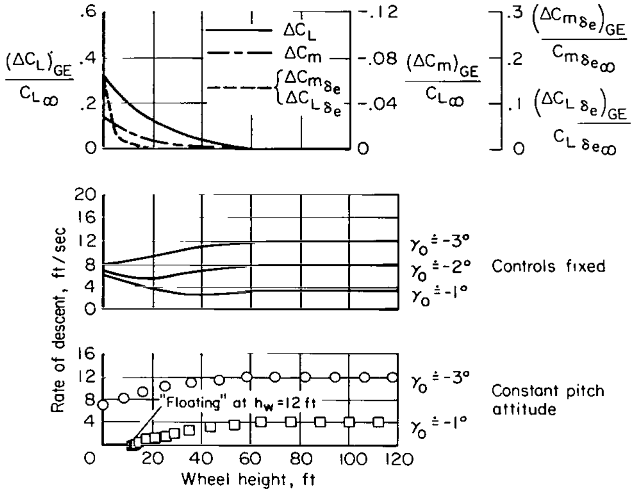


(c) Ground-effect model 3.

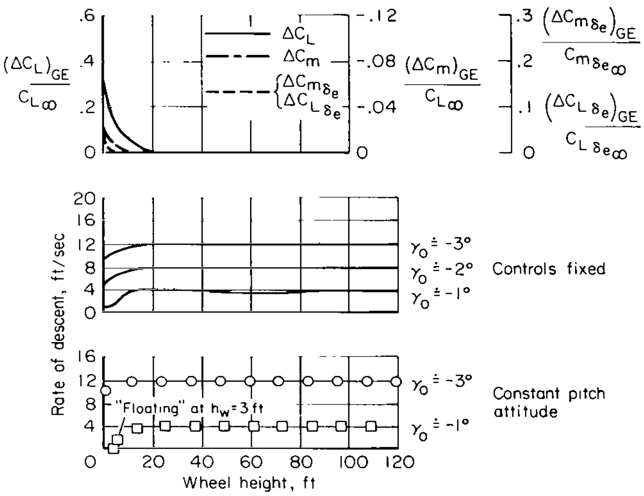
Figure 17.– Computed SST responses to the seven ground-effect models. Initial condition: V = 135 knots, h = 150 ft, γ_0 as shown, trimmed (unaccelerated) flight.



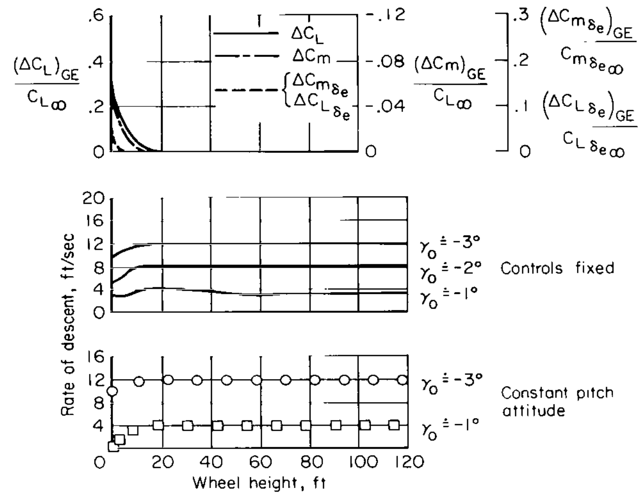
(d) Ground-effect model 4.



(e) Ground-effect model 5.



(f) Ground-effect model 6.



(g) Ground-effect model 7.

Figure 17.– Concluded.

In the absence of pilot input, rate of descent first began to decrease when ground effect was encountered. As the ground-effect moment developed, angle of attack decreased, and rate of descent increased, reaching 20 ft/sec at touchdown, which is nearly twice the current landing gear design limit. This result was independent of initial flight-path angle, as shown by the fact that the plotted descent rates converge as wheel height approaches zero. This is reasonable because the shallow descent angles provide more time per unit altitude change for the pitching moment to integrate into a steepened flight path, thereby approaching the same rate of change of descent rate (and thus the same rate of change of the forcing function, the ground effect) as the initially steeper flight path. Thus the pilot cannot rely completely on the ground cushion to flare an airplane of this size automatically without some means of compensation for the ground-effect pitching moment.

Effect of maintaining constant attitude– If "no-flare" is interpreted to mean maintaining a constant pitch attitude as ground effect is encountered, significant decreases in descent rate *can* be realized for delta-planform airplanes. The constant-attitude runs of figure 17(a) show that descent rate was reduced by ground-effect model 1 from an initial rate of 12 ft/sec to 7 ft/sec. Even greater reductions in descent rate are achievable with other ground-effect models or by airplane modifications that would reduce the lift penalty associated with trimming out the pitching moment.

Effect of L_{δ_e}– A greater reduction in descent rate would have been realized if the airplane had not had an adverse lift due to elevator deflection L_{δ_e}. This can be seen by comparing the constant θ runs of ground effects 1 and 3 (figs. 17(a) and 17(c)). Ground-effect model 3 is identical to model 1 except that the pitching-moment change of model 3 is half that of model 1. Because the aircraft is constrained from pitching through the use of compensating elevator deflection, the differences in these runs are due entirely to L_{δ_e}. An initial descent rate of 12 ft/sec is reduced to 4 ft/sec at zero wheel height by ground-effect model 3, as compared with 7 ft/sec for model 1. Extrapolation of these results would indicate that with zero L_{δ_e}, constant θ landings with model 1 would result in comfortable touchdown sink rates of 1 to 2 ft/sec.

These results appear to offer considerable potential for automatic landings or for simplifying the manual landing task. The adverse L_{δ_e} could be eliminated through the use of a canard or sufficient interconnected direct lift control (DLC), or reduced by the addition of a horizontal tail. Closure of a pitch attitude loop with such a controller could feasibly provide confortable landings with a minimum of complexity. Reference 12 describes a flight investigation which utilized an attitude-stabilized longitudinal control system in combination with DLC. The application of such a combination to large delta aircraft appears to offer considerable merit and is worth additional investigation.

Effect of ground-effect lift leading the pitching moment– An interesting effect is shown by the controls-fixed runs for ground-effect models 2, 4, and 5 (fig. 17(b), (d), and (e)). In each of these cases, the ground-effect lift was encountered at a slightly higher altitude than the pitching moment. Although the ΔC_L is 1/2 the magnitude of that for ground-effect models 1 and 3, the descent rates at zero wheel height are not as severe. On the other hand, the reduction in descent rate is less when θ is held constant with ground-effect models 2, 4, and 5 $[(\Delta C_L/C_{L_\infty})_{max} = 0.32]$ than with 1 and 3 $[(\Delta C_L/C_{L_\infty})_{max} = 0.60]$, because the lift increase is less. These results indicate the importance of defining whether, or under what circumstances the indicated lead in developing lift due to ground effect actually does occur.

Effect of encounter height (airplane size)– Ground-effect models 6 and 7 were programmed to investigate the effect of height at which ground effect is encountered. In both cases, ground effect was first encountered at 18-ft wheel height (approximate encounter height of the F5D-1 airplane as shown in fig. 8). Values of ΔC_m bracket that for the F5D-1 with the magnitude of model 6 one-third that of model 7. The maximum incremental lift coefficients of models 6 and 7 are equal and match the F5D-1 value. Note that there is little difference between the two sets of results. Because there was insufficient height for the pitching moment to be integrated into an increasing descent rate, the primary ground influence was a small reduction in descent rate due to ground-effect lift. This indicates that the ground-effect pitching moment is a less significant factor in the landing flare of small airplanes because of the low height at which ground effect is encountered (and also because of the better control response of smaller airplanes).

The differences due to ground-effect encounter height (result of airplane size) can be readily seen by comparing the analog runs for models 7 and 4, or those of 6 and 5. (Maximum ΔC_L are identical and maximum ΔC_m are of comparable magnitude.) These comparisons show that the consequence of leaving controls fixed is more severe with the higher encounter height, but the advantages from maintaining a constant attitude are greater.

In summary, it appears that the ground effect on large delta-wing airplanes has considerable potential for assisting the landing flare, if proper pitch attitude stabilization is provided and adverse lift due to control deflection is minimized.

Piloted Evaluation of SST Ground-Effect Models

Pilots' observations and ratings– For brevity, the pilots' observations and ratings corresponding to each of the ground-effect models are summarized in table 6. More complete pilot comments are given in appendix C.

TABLE 6.– SUMMARY OF PILOT EVALUATIONS OF SST GROUND–EFFECT MODELS

Ground effect model	Descriptive note	Pilots observations	Average pilot rating
1	Most plausible from wind tunnel studies	Objectionable nose-down pitching moment noticeable prior to normal flare initiation requiring excessive column displacement and force. Less objectionable if anticipated. Little ability to make a good landing accurately and consistently.	5.2
3		Provides a cushioning effect which gives pilot a cue to initiate his flare. Amount of work to flare not excessive. Lift and moment balanced well enough that a very soft landing is possible.	2.7
2	Lift "leads" pitching moment	Initial lift increase apparent with a slightly greater (than model number 1) pitching moment effect as ground is approached. Feels like you don't have as much lift holding up after you're in ground effect for awhile. Control force and deflection objectionably high.	3.9
4		Almost no flare required. If attitude maintained, feels as if airplane will land itself beautifully. Extremely easy to land. Amount of nose-down moment beneficial because it prevents long-term floating.	2.8
5		Ideal situation for an airplane. Ground effect lift acts over such a long period of time that you actually see the sink rate being arrested when you hold constant attitude. Moment effect is so small that it is masked by normal control motions.	2.3
6	Low encounter height	Almost doesn't seem to be any effective ground effect. No problem, just requires the pilot to make necessary attitude change for landing.	2.2
7		Moment change hardly noticeable. Some tendency to float at 160 knots (V_a + 25).	2.6

In general, variations in the ground-effect model within the bands defined for delta-wing aircraft in appendix A can change the initial unsatisfactory rating (ground-effect model 1) to a satisfactory value, including some quite favorable remarks. In addition, evaluation of models 2, 4, and 5 indicated that it was generally beneficial if the lift was encountered slightly higher than the moment change.

If the nose down trim change was noticeable before the pilot would normally initiate the flare maneuver, he found it less acceptable. If it occurred during the flare maneuver, the ground effect was somewhat masked in the dynamics of the maneuver, and the pilot found it much more tolerable. This, along with the comments associated with models 6 and 7, would indicate that ground effect for small delta-wing aircraft would appear less objectionable than for large deltas even though the same maximum control deflection was needed in both cases.

Modifications to the airplane control system or to the landing conditions could serve to improve the poorer pilot ratings above. Increasing the landing speed by 15-25 knots generally improved pilot ratings by 1/2 to 1 whereas reducing landing speed 15 to 25 knots resulted in 1/2 to 1 poorer rating. Shallower approach angles tended to make the flare characteristics more acceptable, presumably because of the reduced rate of onset of the ground effect.

Elevator required to counter ground effect– Because many of the pilot comments were concerned with the large control input required to maintain steady 1 g flight with the SST, an expression was derived indicating the interrelationship between $(\Delta C_m)_{GE}$, $(\Delta C_L)_{GE}$, C_{L_∞}, $C_{m_{C_L}}$, $C_{L_{\delta_e}}$, and $C_{m_{\delta_e}}$.

$$\Delta\delta_{e_{1-g}}(\text{radians}) = -C_{L_{trim}}\left\{\frac{[(\Delta C_m)_{GE}/C_{L_\infty}] - G}{C_{m_{\delta_e}} - \dfrac{C_{L_{\delta_e}}G}{[(\Delta C_L)_{GE}/C_{L_\infty}]}}\right\}$$

where

$$G = \frac{(\Delta C_L)_{GE}/C_{L_\infty}}{1 + [(\Delta C_L)_{GE}/C_{L_\infty}]}\left[\frac{(\Delta C_m)_{GE}}{C_{L_\infty}} + C_{m_{C_L}}\right]$$

and $C_{m_{\delta_e}}$, $C_{L_{\delta_e}}$ include ground-plane influence on control effectiveness. This expression appears useful as a basis of comparison for the various conditions flown, through variations in ground-effect model, approach speed, and static stability. The derivation of this expression and the simplifying assumptions are given in appendix D.

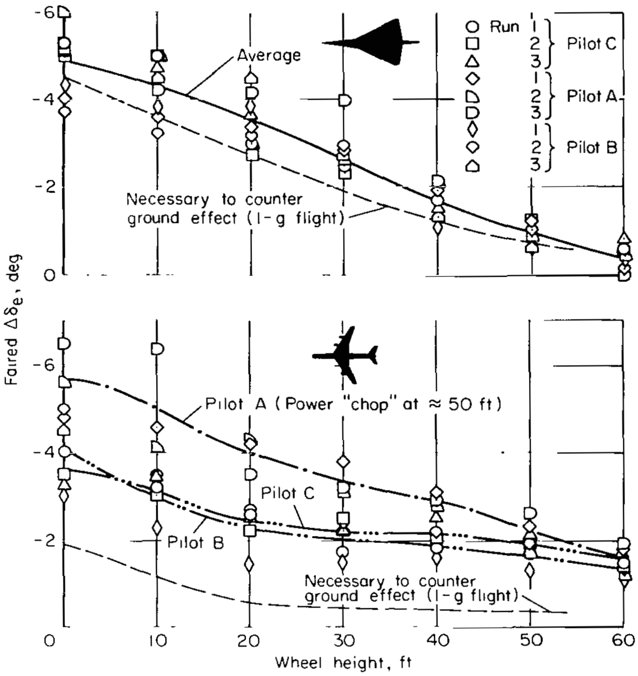


Figure 18.- Elevator deflection versus wheel height from piloted simulator runs. SST: GE model 1, V_a = 135 knots; SJT: V_a = 146 knots.

In order to check the validity of this expression, the computed incremental elevator angle was compared with the recorded elevator deflection from piloted SST and SJT runs. Figure 18 was constructed by fairing through the elevator angle trace and plotting the faired elevator angle versus height at 10-foot increments, with three runs shown for each pilot. It was expected that the computed $\Delta\delta_e$ values (shown by the dashed lines) would be less than the piloted values because the computed runs are for 1 g no-flare flight. Because of the low static longitudinal stability of the SST, this difference was small as expected.

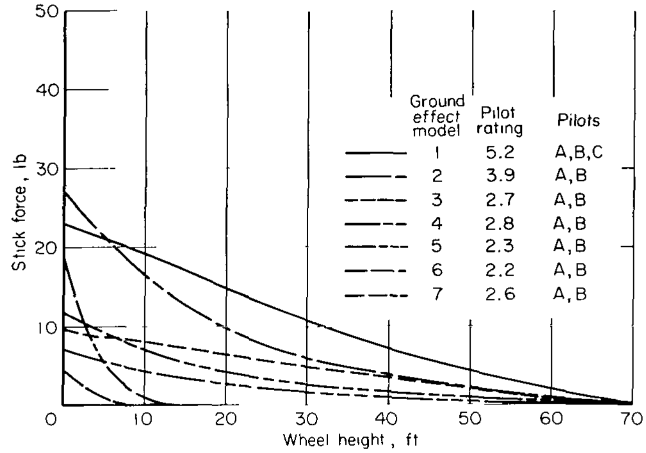
The SJT, on the other hand, had relatively high static stability, and more elevator was used to flare the airplane than was necessary to counter the ground effect. Differences in thrust-management techniques made it necessary to average each pilot's runs separately. Reductions in thrust required additional elevator because of the thrust pitching moment and lessening speed; this is especially evident in the runs flown by pilot A who abruptly reduced power at 50 to 60 feet wheel height. High static longitudinal stability therefore tends to mask the ground-effect elevator requirement due to high F_s/g to flare and the increased elevator requirement due to the reduction in speed.

Correlation of column force with pilot rating— Although many factors influence acceptability of an airplane's flare characteristics, column force appears to be one of the more dominant. Therefore, correlation between the pilot ratings and the required column force was investigated for the various conditions flown. Using the equation introduced in the preceding section, the elevator required to counter ground effect was computed for each of the conditions flown. Because the SST simulation utilized a nonlinear column-to-elevator gearing, the elevator angles were converted to the equivalent column forces and plotted versus height in figure 19. Also shown on the figure is the corresponding average pilot rating for each condition.

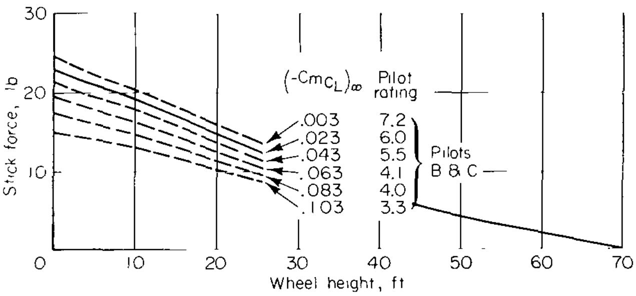
In order to increase the sample size, results are included from a series of landings in which the free-air static longitudinal stability was varied from -0.003 to -0.103. This was not equivalent to a CG shift because the ground-effect model (no. 1) was unchanged.[2]

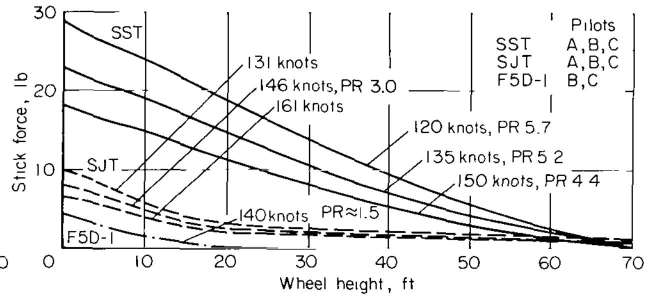
[2] A CG shift requires a modified $(\Delta C_m)_{GE}/C_{L_\infty}$ value for each CG position.

$$\left[\frac{(\Delta C_m)_{GE}}{C_{L_\infty}}\right]_{\text{modified}} = \left[\frac{(\Delta C_m)_{GE}}{C_{L_\infty}}\right]_{\text{basic}} + \frac{(\Delta C_L)_{GE}}{C_{L_\infty}} \Delta C_{m_{C_L}}$$



(a) Comparison of seven SST ground-effect models.





(b) Effect of SST static longitudinal stability $(C_{m_{C_L}})_\infty$, ground-effect model 1.

(c) Comparison of SST, SJT, and F5D-1 ground effect showing effect of landing speed. SST GE model 1.

Figure 19.– Stick force required to maintain 1-g flight in ground effect, shown with corresponding pilot rating (Cooper scale) numbers.

The data of figure 19 were cross-plotted in figure 20 to show pilot rating versus the maximum (zero wheel height) column force. The seven basic ground-effect models are represented by the unshaded symbols. Results from the varied $C_{m_{C_{L_\infty}}}$ tests (using ground-effect model 1) are shown as shaded circles. Results from the speed variation runs (with model 1) are shown as half-shaded circles. The flagged symbols denote ground effect with a low encounter height.

The data of figure 20 appear to fall within three general groupings. Those points in which the nose-down trim change was evident prior to initiation of the flare (ground-effect models 1 and 3) proved to be the more objectionable – that is, the adverse characteristics were most apparent and yielded the highest (poorest) pilot ratings. Crossover of the 3-1/2 boundary indicates that when the nose-down trim change is apparent prior to normal flare initiation and the maximum force required is greater than 16-18 lb, the ground effect will be objectionable (unsatisfactory). However, if the trim change is masked by normal flare inputs, pilots will tolerate ground-effect control sensitivity combinations requiring up to 21-23 lb before considering them objectionable.

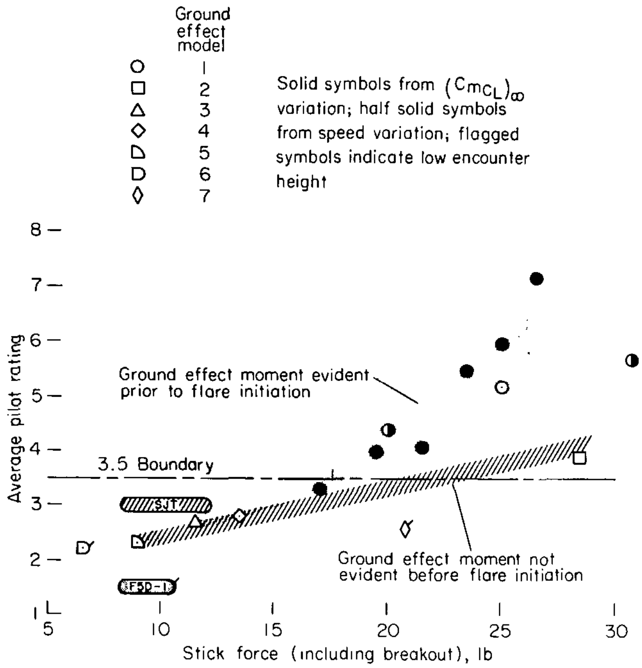


Figure 20.– Cross plot from figure 19 showing pilot rating versus the maximum stick (column) force required to counter ground effect. Fixed-base simulator results.

The location of the flagged symbols of figure 20 indicates that for smaller aircraft where ground effect is encountered in the final 20-30 feet, considerably higher stick force requirements will be tolerated.

Note that the SJT points fall outside the bands, but if corrected for the added forces required to flare this airplane (as indicated in fig. 18), about 10 lb can be added to the force and thus place the SJT points very near the second (striped) band.

While these results define quantitative acceptability limits on the column force required to counter ground effect, it is possible that with the added motion and visual cues of actual flight, pilots might tolerate somewhat higher force requirements than those indicated by figure 20.

CONCLUSIONS

A piloted fixed-cockpit simulator study has been conducted to investigate the landing flare characteristics of an *unaugmented* tailless delta-wing supersonic transport configuration, and in particular, the ground effect. The results of this study allow the following conclusions to be drawn.

1. Ground effect appears to have greater significance as airplane size increases, because of the region of influence extending to greater heights above the surface.

2. The significant ground-effect lift of the large delta airplane appears to possess considerable potential for assisting the landing flare, for either the manual landing or automatic landing task, if proper pitch stabilization is provided and the adverse lift due to control deflection can be eliminated. Results indicate that descent rate reductions of nearly 100 percent may be feasible if a constant pitch attitude is maintained as the ground is approached.

3. Because of the ground-effect nose-down pitching moment, leaving controls fixed during entry into ground-effect results in touchdown vertical velocities great enough to cause structural damage, regardless of the approach angle.

4. The tailless delta SST without control augmentation was considered acceptable for emergency operation landings but would require augmentation to make it satisfactory for

normal operation. Due to delayed flight-path response, poor attitude stability, and a significant ground-effect pitching moment, flight-path adjustments were not possible with the precision attainable with the subsonic jet transport. In addition, the pilot's location well ahead of the wheels combined with the adverse effects of elevator control on lift made precise judgment of wheel height and height rate more difficult with the simulated SST.

5. Qualitative assessments of ground effect appear to be strongly influenced by the column force required during the flare and whether the nose-down trim change is apparent prior to initiation of the flare. Pilot opinion ratings *from the simulator* show that for an acceptable rating for an airplane of SST size, the maximum column force required to counter ground effect should be less than 16 pounds.

6. Additional factors which provided some alleviation of the severity of the ground-effect trim change included (1) higher landing speeds, (2) shallower approach angles, and (3) pilot anticipation of the trim change.

7. Pilots showed a preference for a ground effect model in which the lift change was encountered at a slightly higher altitude than the pitching moment change. Thus, it appears worthy of additional investigation to define whether, or under what circumstances, the indicated lead in developing ground-effect lift actually does occur.

8. An equation was derived that allows simple computation of the elevator deflection required to maintain 1 g flight at various heights above the ground. The equation made it possible to determine the total elevator required versus height from a combination of different height factors associated with the ground effect lift, pitching-moment, and control-effectiveness changes. The total elevator required is useful as a subjective measure of ground effect.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California, 94035, April 29, 1970

APPENDIX A

VALIDITY OF SST GROUND-EFFECT REPRESENTATION

One of the factors listed as questionable in the Introduction was the validity of the data used to program the SST ground effect. This section discusses the magnitude of ground effect on delta-like planform wings and the range of scatter in the existing data. Flight correlations of wind-tunnel measurements for the modified F5D-1 and XB-70 airplanes are included.

Compilation of Wind–Tunnel Data

A considerable quantity of information on ground effect on delta-like wings was found to exist; these lift and pitching-moment data are plotted in figure 21. Simulated ground-effect models 1, 2, and 3 are included for comparison. When normalized to C_{L_∞}, corrected to a common $C_{m_{C_{L_\infty}}}$, and plotted versus $h/\bar{c}$, the data, although from various sources, show a remarkable degree of consistency. All exhibit the same trend of increased lift and nose-down pitching moment in ground effect, with the values increasing with decreasing height. Lift increments at touchdown ($h/\bar{c} = 0.2$ for the subject configuration) range from about 40 to over 65 percent. Ratio of incremental pitching moment (at constant α) to out-of-ground lift coefficient, $(\Delta C_m)_{GE}/C_{L_\infty}$ ranges from -0.07 to -0.12 at touchdown. Differences in values corresponding to the scatter shown in the data can make a significant difference in the pilot's subjective evaluation of the airplane's flare characteristics, as indicated in the Results and Discussion. Comparative values for the subsonic jet transports with swept wings of moderate aspect ratio (6-8) and in the landing configuration are of the order of 0 to 25 percent incremental lift increase and $(\Delta C_m)_{GE}/C_{L_\infty}$ of -0.05 to -0.10 as shown in figure 9.

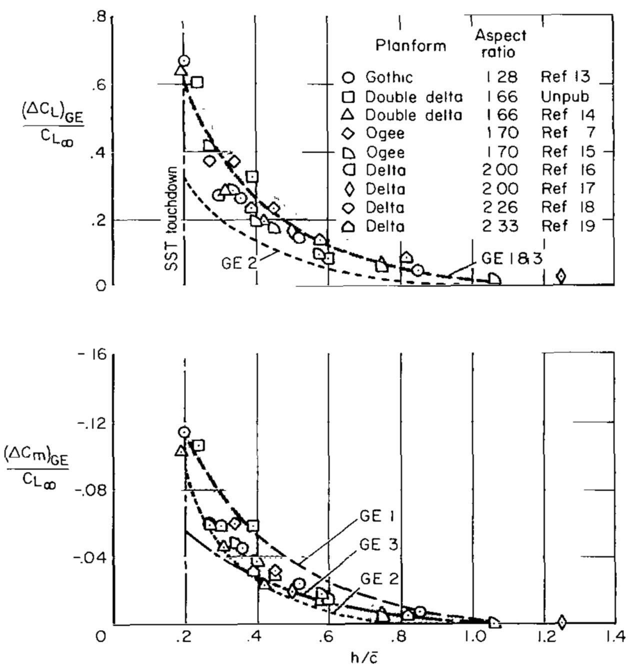


Figure 21.– Compilation of wind-tunnel data on ground-effect lift and pitching moment for several delta-like configurations. Data corrected to $C_{m_{C_{L_\infty}}} = -0.023$.

There is some indication in figure 21 of the ground-effect lift being encountered at a greater altitude than the pitching moment, an event which was shown in the Discussion section to have considerable subjective significance.

Correlation of flight and wind-tunnel-measured ground effects on the modified F5D-1 used in this study is reported in reference 6. In reference 6 flight measurements based on constant altitude fly-bys are compared with wind-tunnel data from three different facilities. The results, shown in figure 22, show reasonable correlation among the lift data and fair correlation in the moment data. Flight-measured moments were only about 60-75 percent of the wind-tunnel values. The lift data and the wind-tunnel moment data define bands which fall within the scatter of delta-wing data of figure 21, thereby tending to confirm those data.

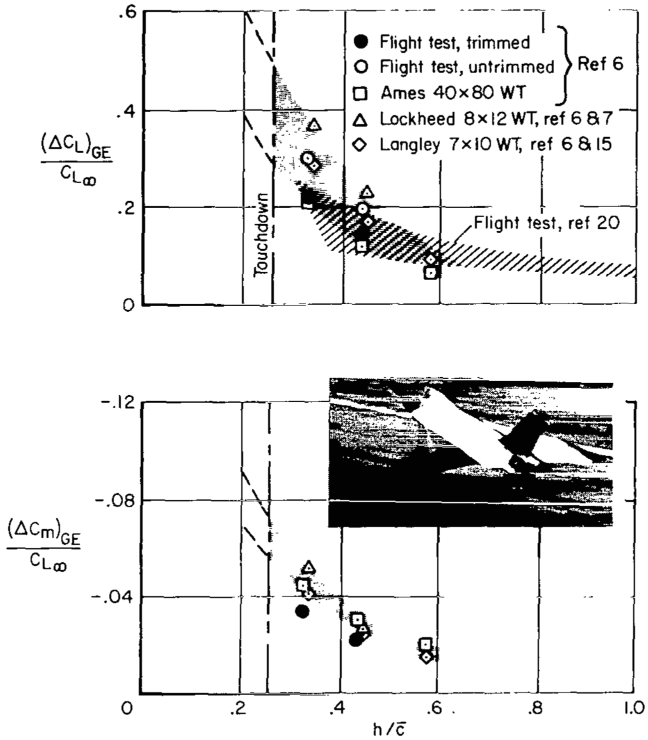


Figure 22.– Comparison of F5D-1 (modified) ground effect from wind-tunnel and flight-test measurements. Data corrected to $C_{m_{C_{L_\infty}}} = 0$.

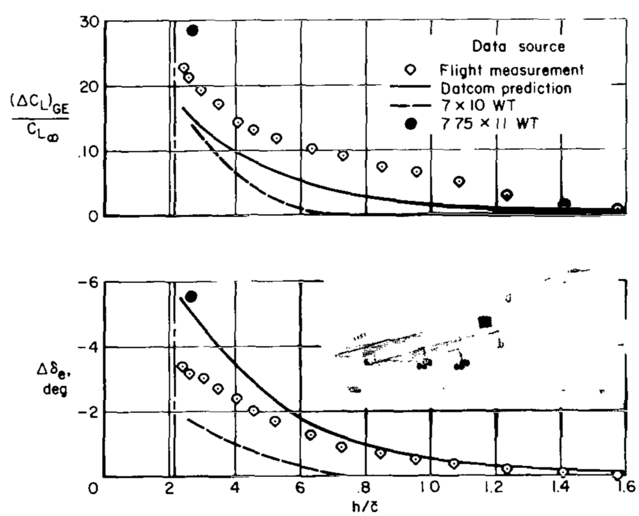


Figure 23.– Comparison of flight, wind tunnel, and theoretical ground-effect data for XB-70 airplanes at 9.3° angle of attack (ref. 20).

Flight measurements of ground effect on several low-aspect-ratio airplanes, using a constant angle-of-attack technique, were recently reported in reference 20. The results for the ogee F5D-1, one of the airplanes in that study, are included in figure 22 and indicate one of the findings of that study. Ground-effect lift was found to extend consistently to heights greater than one wing span above the ground. Reference 20 theorizes that wind-tunnel-measured ground effects tend to go to zero prematurely because of the negative effects produced by the ceiling of the tunnel. Possible effects of the higher lift-encounter height might be to improve the pilot's subjective impression while increasing the landing distance. It seems advisable that future landing simulations based on wind-tunnel data consider the encounter height as a test variable.

Flight measurements, wind-tunnel measurements, and predicted values of ground effect for the North American XB-70, a large delta-wing airplane with 1.75 aspect ratio, are compared in reference 20 and shown in figure 23. Flight measurements fall between the wind-tunnel measurements. The incremental lift increase is about 25 percent at touchdown ($h/\bar{c} = 0.215$) and requires about 4° of elevator to maintain 9.3° angle of attack. The corresponding value of $(\Delta C_m)_{GE}/C_{L_\infty}$ is estimated to be about -0.04. It would be slightly greater if the ground effect on elevator control effectiveness were accounted for. This combination of lift and pitching moment is near GE model 4; pilot comments regarding XB-70 ground effect and SST GE model 4 are favorable and similar.

Flight measurements on the ogee F5D-1 and the XB-70 showed ground effects of approximately one-half that of GE model 1, the primary ground effect used for the SST in this study. However, both the XB-70 and the F5D-1 demonstrated reasonable agreement with wind-tunnel results, and a significant amount of tunnel data exists to support GE model 1 for a double-delta SST. GE model 1 probably represents an upper bound on SST ground effects, and use of it in this study was conservative in that it presented the most demanding task.

APPENDIX B

ADEQUACY OF SIMULATOR FOR TASK PRESENTATION

The landing flare and touchdown task has been found difficult to portray accurately in simulators. Without cockpit motion, an added burden is placed on the fidelity of the visual display to compensate, to some degree, for the missing motion stimuli.

All participating pilots were requested to comment on the visual scene and on the adequacy of the cues available to them. The following quotations reflect their opinions.

(During simulated F5D-1 landings) "The touchdown and flare as shown in this display are extremely realistic. I would say that everything that I am doing is done in the manner that I would do it in flight except, of course, for the absence of motion cues which right now don't seem to be very important."

(With the SJT simulation) "With the SJT cockpit height, the visual display is extremely effective for control of touchdown sink rate. It is important to note that the ability to judge height and control touchdown is very similar to the actual flight situation with this aircraft attitude and simulated cockpit height. This ability deteriorates rapidly as a higher cockpit height is simulated. The conditions for judgment appear to be poorer, or to get poorer faster (with increasing height) on this display than they do in the real world. An increase in cockpit height in the real world isn't going to be in the desirable direction, but the effects are probably magnified in the simulator. It is harder to see detail on the runway and to be able to detect height and height rate. With the SJT simulation, the flare is not being done mechanically and the ability to hold the airplane off (delay touchdown) is quite realistic."

Or as summed up by another pilot:

"The visual cues are adequate for interpreting the flare, even though they are not identical to visual flight. However, they do help to identify the problems that you can get into with this (delta SST) configuration when attempting to get smooth landing and low touchdown velocities . . . . It is harder to detect increases in sink rate; using the simulator display, you can do it but there is more feeling of lag, compared to doing it in the clear real-world situation."

These pilot evaluations show that the quality of the visual display compensated adequately for the lack of motion for the F5D-1 and SJT simulations as indicated by the fact that landings were completed within real world touchdown criteria without the need for techniques peculiar to the simulation. More comments regarding response lags were observed during the SST tests and the discussions indicated that the lack of motion cues was more important when the simulated airplane was significantly different from any that the pilot had previously flown. Although it seemed to take somewhat longer to adapt to the simulation of a strange airplane, possibly because of the lack of motion, the pilots indicated that their comparative evaluations of the landing characteristics were valid.

The ability to judge height and perceive changes in sink rate appeared to undergo some deterioration as higher cockpit conditions were simulated; whether this was due to the higher cockpit or a shortcoming of the visual display was not resolved. This degradation was not considered critical by any of the participants. In fact, SST landings were found extremely easy for certain ground-effect models investigated, an unlikely result had the visual cues been seriously deficient.

Lack of motion cues and less-than-ideal visual cues can serve to amplify the effects of the apparent nose-down trim change due to ground effect. Without these cues, the onset of disturbances (such as ground effect) and control response is not as immediately apparent and overcontrolling can result. It is recommended that additional studies be conducted to determine the influence of vertical and pitch motions on the subjective evaluation of the landing flare. In addition to its value in the interpretation of fixed-base simulator results, this information is needed for use in specifying requirements for airline training simulators.

APPENDIX C

PILOT COMMENTS FROM SST GROUND-EFFECT MODEL COMPARISONS

Ground-Effect No. 1

Pilot A– At 135 knots, there does not appear to be any noticeable ground cushion nor tendency of the airplane to flare itself. It does require flare by the pilot; however, there appears to be no significantly objectionable ground effect. As long as you initiate your flare before you're captured by ground effect, it's not particularly noticeable but if you delay, let it fly on down through and make a late flare in recovery, it feels as though it takes too much force and too much elevon; you can't move the airplane fast enough, pilot rating 3-1/2 to 4.

As a rule, making an initial flare before cutting the power back enables you to minimize any nose-down trim change. The best procedure is to leave the power on. This is optimum technique with most delta-wing airplanes at low aspect ratio.

At 120 knots there appeared to be a greater combination of effective ground effect and inability to flare with net result that sink rate was fairly high. Attitude stability is degraded at the low speed resulting in unsatisfactory flare characteristics, pilot rating – 4.

There was some decrease in the required stick forces at the higher speeds, Pilot rating – 3 to 3-1/2.

Pilot B– The ground-effect moment is pronounced and noticeable and occurs over such a long time period that even though you are in the process of flaring, you have the feeling that it is requiring considerable back motion and force on the control column in order to just maintain your present position (flight path). It requires even more than that, of course, to flare. It is much more severe magnitude and much more pronounced than on any existing airplane in that it would be impossible for one to fly this without noticing the fact that it was there. Whereas, it is quite impossible for most pilots to even detect the ground effect unless somebody describes it to them on any of the airplanes that we've been flying.

The nose-down moment is much more noticeable at the lower speed. At 120 knots it seems as though an undue amount of aft control was required just to maintain normal attitude. It doesn't seem like a flare can be generated reasonably well at this speed with the apparent nose-down moment here. At 110-115 knots, it definitely feels like the bottom is dropping out from underneath the airplane and it really rotates down – it's quite hard to hold and I'm sure it would be very difficult to keep from having bad landings.

Ground effect is reduced at the higher speeds; I imagine it would just require less elevator force and deflection to get it to respond. I still found it quite objectionable. That is, the nose-down moment occurred and it was noticeable prior to the point at which I would normally apply controls to reduce the sink rate for flare and so it does give the feeling that it is diving for the deck.

At the lower speeds, it's grim and I would rate it unacceptable (pilot rating greater than 6). At 160-170 knots, I would still call it unsatisfactory; the rating would be about 5.

Pilot C– The ground effect appears to be very strong and it is very difficult to accurately control the attitude or sink rate close to the ground. The flare characteristics, as I see them on this configuration, are not satisfactory. I could not tell what my touchdown was, but the pitching moment seemed to be rather excessive. Longitudinal response to elevator inputs was satisfactory. I would rate the ground effect about a 6 from what I see in the simulator. There is little ability to accurately and consistently make a decent landing. If there was any distraction during this period, it would crash to the ground. Rating at 120 knots, 6, and 150 knots, 5.

Ground-Effect No. 2

Pilot A– The initial lift increase is apparent. This seems to have a slightly greater pitching moment effect; or conversely less lift increase as you approach close to the ground. It feels like you don't have as much lift holding up after you're in it (ground effect) for awhile. The elevon deflection and force required are objectionably high on this one. It seems to want to dive in the last few feet.

At the higher speed, the initial increase in lift is a little more pronounced but also the nose drop before I got on the ground wasn't too good.

Having the pitching moment come in late and lift effects early is beneficial in general. Pilot rating 3.7.

Pilot B– That condition (nose-down trim change) is not noticeable at 160-170 knots. You are already in the flare and the control effectiveness is so high that you get very good flare response and the moment isn't even noticeable. At 160-170, I'd rate it about a 2.

At 135 knots you can notice it. However, it is occurring after the normal flare has been initiated and I wouldn't consider it very serious. It would probably cause some difficulty and you would rather it wasn't as strong as it is. Would call it about a 4 rating.

At 120 knots, it is about the same thing. Pilots would be aware of it and would be able to comment without being asked if it reacted the way this simulation does.

Ground-Effect No. 3

Pilot A– Initial runs resulted in tendency to overflare. It could just be adapting to the new ground effect which apparently must be giving me more lift. There seems some getting used to the different timing on the flare and rate. This one feels better in many respects because I do notice a tendency to flare which has the value of giving you a cue for your own flare. Now, as I reduce the overcontrolling tendency, it takes very little elevon brought in at the right instant to complete the flare.

At 120 knots, the nose-down trim change was more apparent; I didn't detect the lift quite as much but variations in control of flight path can influence this. The nose-down trim change seemed milder (compared to GE No. 1) on this configuration in general.

At the higher speeds, improved controllability in pitch has its effect in minimizing the ground-effect adverse characteristics as far as trim change goes.

There was definitely improvement over ground-effect number 1, almost inclined to call it satisfactory; however, think I'll leave it at 3-1/2 rating.

Pilot B– The ground effect that we have in here now is fairly acceptable. This is all right. Even the amount of work that I have to do to flare isn't excessive by any means and there is a cushioning effect too. There is a lift increase and a moment; they seem to be balanced well enough so that a very soft landing is possible.

I'm a little concerned with the nose-down moment at the very low-speed condition – even here you can readily control it. At 135 knots, it is not even noticeable. At 160 knots, there is no ground effect and I would rate it as 1 to 2 at those speeds. However, it is just about a 3 to 4 at the lowest speed condition (110 knots) because here it looks like, if you don't concern yourself with it, the airplane would really touch down hard. At this end point condition, the low speed acts like the F5D; but it is more pronounced in that you can really see it here. Like the F5D, if you fix the controls, then it will do what this simulation does; but this simulation will start to do it even if you are coming back on the control column. But it is hardly worth downgrading significantly. It is there, but if you fly a good approach at this low speed, it is possible with just normal landing procedures to make a soft touchdown. I would rate it a 3 to 4 at this test speed and 1 to 2 for 135 knots and above.

Ground-Effect No. 4

Pilot A– Trim changes are milder on these. You don't notice it if you have started the control against it, that is started to rotate the airplane – but it's still there. With the lift coming in early, you nearly get a flared attitude without any input. I feel that GE No. 3 was somewhat better; it seemed to float more on that one. I call this one a 3-1/2.

Pilot B– This ground effect (over the entire speed range) is dominated by the lift effect. That is, the moment change is somewhat insignificant from the pilot's point of view on the simulation. The lift effect gives a marvelous cushion so that landing zero-zero would be exceptionally easy with this situation. In fact, almost no flare is required. In this characteristic, it is like the F5D, in that if you simply held the attitude that you have during the stabilized portion of the approach, the airplane will land itself beautifully. Now, some back pressure is required to hold that attitude because there is a slight nose-down moment, but you really don't notice that since you are simply trying to hold the aircraft attitude relatively constant and you see that as you approach the ground, the sink rate is reduced by the ground effect and the airplane is extremely easy to land. I would rate this ground effect as being 1 to 2 throughout the speed range. I think it (the nose-down moment) is beneficial because it prevents a long-term floating.

Ground-Effect No. 5

Pilot A– This one seemed to have a reasonable increase in lift preceding touchdown early in the flare and then took a very, very slight force for further increase in attitude. You can just hold your attitude and it bleeds off nice without any noticeable trim change.

At the lower speed we got a very definite increase in lift that helped cushion our landing, then there was a pitching moment. At the higher speed, ground effect wasn't too noticeably different, slightly better.

This has mildly objectionable trim changes you can notice under some conditions. Presents no real problem though. I'd generally rate this with a 3.

Pilot B– I couldn't really say much different about this from configuration 4. My first impression is that this seems better, but I don't think I could really tell the difference between the two if switched back and forth. The moment effect is so small that normal control motions seem to create more aircraft pitch motion when ordinarily just flying than does the ground-effect pitching moment. So this is probably much closer to the F5D sort of thing in that normally the pilots would never even know that there was a moment effect. However, when flying that small airplane (the F5D), you don't really see the arrest of the sink rate as well as you do on this one. On this one, lift seems to act on over such a long period of time that you actually see the sink rate being arrested by the ground effect when you hold a constant attitude passing down through 50-40 feet. There is no necessity to further flare the airplane, simply holding what you have does just fine. This would be an ideal situation for an airplane.

Ground-Effect No. 6

Pilot A– There almost doesn't seem to be any effective ground effect. It just requires the pilot to make the necessary change in attitude for landing and it's no problem. No noticeable trim changes or lift effects. I'll rate it a 3.

Pilot B– The moment seems to have less effect than I was able to notice on the F5D. So, for all intents and purposes, the moment change doesn't exist on this configuration. The increase in lift is still noticeable and it is possible to simply hold attitude all the way through to touchdown and end up with an acceptable sink rate reduction prior to ground contact over the entire speed range from 120 to 160 knots. Pilot rating is 1-2.

Ground-Effect No. 7

Pilot A– At the lower speed, the degradation in flight path control is sufficient to make it difficult to detect ground effect.

At the higher speeds in general, I have the feeling that I can start a smooth change in attitude and stop it when I've got the right amount, just hold it and get a reasonable touchdown without any problems. Pilot rating: low speed, around 4; 135 knots, 3.3; high speed, 3 or better.

Pilot B— There is a marked tendency to float at 160 knots with the lift increase that this has. The increase in moment is hardly noticeable. I did notice the moment at 110-115 knots, but so insignificant as not to bother with. I didn't really even notice it at 135 knots.

I would rate this as 2 at 110-120 knots and 1-2 at 135-160 knots.

APPENDIX D

DERIVATION OF AN EQUATION FOR CALCULATING THE ELEVATOR DEFLECTION REQUIRED TO COUNTER GROUND EFFECT

In order to analyze the results from the studies utilizing a variety of ground-effect representations and airplane characteristics, it proved useful to derive an expression for the elevator deflection required to maintain 1 g (unaccelerated) flight as a function of $(\Delta C_L)_{GE}$, $C_{L_{trim}}$, $C_{m_{C_L}}$, $C_{m_{\delta_e}}$, and $C_{L_{\delta_e}}$. This was done by first writing the vertical and pitching equations of motion, imposing the constraints of wings-level unaccelerated flight, and then simplifying to perturbation equations in terms of $\Delta\alpha$ and $\Delta\delta_e$. These equations were then combined into the desired single equation for $\Delta\delta_e$. The vertical and pitching equations of motion are given by:

$$a_z = g \cos\phi - \frac{T}{m}\sin(\alpha + i_T) - \frac{\rho V^2 S}{2m}\left[C_{L_o} + C_{L_\alpha}\alpha + C_{L_{\delta_e}}\delta_e + (\Delta C_L)_{GE}\right] - \frac{\rho V S \bar{c}}{4m}\left(C_{L_q} q + C_{L_{\dot{\alpha}}}\dot{\alpha}\right) \tag{1}$$

$$\dot{q} = \frac{\rho V^2 S \bar{c}}{2I_y}\left[C_{m_o} + C_{m_\alpha}\alpha + C_{m_{\delta_e}}\delta_e + (\Delta C_m)_{GE}\right] + \frac{\rho V S \bar{c}^2}{4I_y}\left(C_{m_q} q + C_{m_{\dot{\alpha}}}\dot{\alpha}\right) + \frac{d}{I_y}T + \left(\frac{I_Z - I_X}{I_y}\right) rp \tag{2}$$

For wings-level flight:

$$\phi = r = p = 0, \quad \cos\phi = 1$$

For unaccelerated flight:

$$a_Z = \dot{q} = 0$$

Require that the airplane be initially in trim. It follows that $q = 0$. Assume $(\alpha + i_T)$ is a small angle such that $\sin(\alpha + i_T) \approx \alpha + i_T$. Assume $\dot{\alpha}$ contributions negligible.

Incorporating these conditions, we rewrite the equations:

$$0 = g - \frac{T}{m}(\alpha + i_T) - \frac{\rho V^2 S}{2m}\left[C_{L_o} + C_{L_\alpha}\alpha + C_{L_{\delta_e}}\delta_e + (\Delta C_L)_{GE}\right] \tag{1a}$$

$$0 = \frac{d}{I_y}T + \frac{\rho V^2 S \bar{c}}{2I_y}\left[C_{m_o} + C_{m_\alpha}\alpha + C_{m_{\delta_e}}\delta_e + (\Delta C_m)_{GE}\right] \tag{2a}$$

The conversion to perturbation equations is accomplished in the following manner.

Assume constant thrust.

Replace α with $\alpha_o+\Delta\alpha$, δ_e with $\delta_{e_o}+\Delta\delta_e$, $C_{L_{\delta_e}}$ with $C_{L_{\delta_{e_o}}}+\Delta C_{L_{\delta_e}}$, and $C_{m_{\delta_e}}$ with $C_{m_{\delta_{e_o}}}+\Delta C_{m_{\delta_e}}$:

$$0 = g - \frac{T}{m}(\alpha_o + \Delta\alpha + i_T) - \frac{\rho V^2 S}{2m}\left[C_{L_o} + C_{L_\alpha}(\alpha_o + \Delta\alpha) + \left(C_{L_{\delta_{e_o}}} + \Delta C_{L_{\delta_e}}\right)(\delta_{e_o} + \Delta\delta_e) + (\Delta C_L)_{GE}\right] \tag{1b}$$

$$0 = \frac{d}{I_y} T + \frac{\rho V^2 S\bar{c}}{2I_y}\left[C_{m_o} + C_{m_\alpha}(\alpha_o + \Delta\alpha) + \left(C_{m_{\delta_{e_o}}} + \Delta C_{m_{\delta_e}}\right)(\delta_{e_o} + \Delta\delta_e) + (\Delta C_m)_{GE}\right] \tag{2b}$$

Further, the initial conditions for the airplane in trimmed flight out-of-ground effect enable us to write:

$$0 = g - \frac{T}{m}(\alpha_o + i_T) - \frac{\rho V^2 S}{2m}\left(C_{L_o} + C_{L_\alpha}\alpha_o + C_{L_{\delta_{e_o}}}\delta_{e_o}\right)$$

$$0 = \frac{d}{I_y} T + \frac{\rho V^2 S\bar{c}}{2I_y}\left(C_{m_o} + C_{m_\alpha}\alpha_o + C_{m_{\delta_{e_o}}}\delta_{e_o}\right)$$

Thus these terms can be eliminated from equations (1b) and (2b), producing perturbation equations.

$$0 = -\frac{T}{m}\Delta\alpha - \frac{\rho V^2 S}{2m}\left[C_{L_\alpha}\Delta\alpha + \left(C_{L_{\delta_{e_o}}} + \Delta C_{L_{\delta_e}}\right)\Delta\delta_e + \Delta C_{L_{\delta_e}}\delta_{e_o} + (\Delta C_L)_{GE}\right] \tag{1c}$$

$$0 = \frac{\rho V^2 S\bar{c}}{2I_y}\left[C_{m_\alpha}\Delta\alpha + \left(C_{m_{\delta_{e_o}}} + \Delta C_{m_{\delta_e}}\right)\Delta\delta_e + \Delta C_{m_{\delta_e}}\delta_{e_o} + (\Delta C_m)_{GE}\right] \tag{2c}$$

When equation (1c) is divided by $\rho V^2 S/2m$ and (2c) by $\rho V^2 S\bar{c}/2I_y$ and the terms rearranged:

$$(C_j + C_{L_\alpha})\Delta\alpha + \left(C_{L_{\delta_{e_o}}} + \Delta C_{L_{\delta_e}}\right)\Delta\delta_e + \Delta C_{L_{\delta_e}}\delta_{e_o} + (\Delta C_L)_{GE} = 0 \tag{1d}$$

$$C_{m_\alpha}\Delta\alpha + \left(C_{m_{\delta_{e_o}}} + \Delta C_{m_{\delta_e}}\right)\Delta\delta_e + \Delta C_{m_{\delta_e}}\delta_{e_o} + (\Delta C_m)_{GE} = 0 \tag{2d}$$

We can further simplify by recognizing that $\Delta C_{L_{\delta_e}} \delta_{e_o}$ and $\Delta C_{m_{\delta_e}} \delta_{e_o}$ are "second-order small" and negligible in comparison with the other terms. In addition $C_j << C_{L_\alpha}$ (e.g., approach C_j is approximately 0.1 to 0.2 and C_{L_α} is approximately 3.0 to 6.0).

$$C_{L_\alpha} \Delta\alpha + C_{L_{\delta_e}} \Delta\delta_e + (\Delta C_L)_{GE} \doteq 0 \tag{1e}$$

$$C_{m_\alpha} \Delta\alpha + C_{m_{\delta_e}} \Delta\delta_e + (\Delta C_m)_{GE} \doteq 0 \tag{2e}$$

However,

$$(\Delta C_L)_{GE} = \frac{(\Delta C_L)_{GE}}{C_{L_\infty}} \left(C_{L_{trim}} + C_{L_\alpha} \Delta\alpha \right)$$

$$(\Delta C_m)_{GE} = \frac{(\Delta C_m)_{GE}}{C_{L_\infty}} \left(C_{L_{trim}} + C_{L_\alpha} \Delta\alpha \right)$$

where the coefficients $(\Delta C_L)_{GE}/C_{L_\infty}$ and $(\Delta C_m)_{GE}/C_{L_\infty}$ are functions of altitude.

Substituting into (1e) and (2e) and grouping factors of $\Delta\alpha$ we have:

$$\left[1 + \frac{(\Delta C_L)_{GE}}{C_{L_\infty}} \right] C_{L_\alpha} \Delta\alpha + C_{L_{\delta_e}} \Delta\delta_e + \frac{(\Delta C_L)_{GE}}{C_{L_\infty}} C_{L_{trim}} = 0 \tag{1f}$$

$$\left[\frac{(\Delta C_m)_{GE}}{C_{L_\infty}} C_{L_\alpha} + C_{m_\alpha} \right] \Delta\alpha + C_{m_{\delta_e}} \Delta\delta_e + \frac{(\Delta C_m)_{GE}}{C_{L_\infty}} C_{L_{trim}} = 0 \tag{2f}$$

If equation (1f) is divided by $\left\{ 1 + [(\Delta C_L)_{GE}/C_{L_\infty}] \right\} C_{L_\alpha}$ and the terms rearranged

$$\Delta\alpha = - \frac{C_{L_{\delta_e}} \Delta\delta_e + \dfrac{(\Delta C_L)_{GE}}{C_{L_\infty}} C_{L_{trim}}}{\left[1 + \dfrac{(\Delta C_L)_{GE}}{C_{L_\infty}} \right] C_{L_\alpha}}$$

Substituting into (2f), noting that $C_{m_\alpha}/C_{L_\alpha} = C_{m_{C_{L_\infty}}}$, and solving for $\Delta\delta_e$, we obtain:

$$\Delta\delta_e(\text{radians}) = -C_{L_{trim}} \left[\frac{\dfrac{(\Delta C_m)_{GE}}{C_{L_\infty}} - G}{C_{m_{\delta_e}} - \dfrac{C_{L_{\delta_e}} G}{\dfrac{(\Delta C_L)_{GE}}{C_{L_\infty}}}} \right]$$

where

$$G = \frac{\dfrac{(\Delta C_L)_{GE}}{C_{L_\infty}}}{1 + \dfrac{(\Delta C_L)_{GE}}{C_{L_\infty}}} \left[\frac{(\Delta C_m)_{GE}}{C_{L_\infty}} + C_{m_{C_{L_\infty}}} \right]$$

and $C_{m_{\delta_e}}, C_{L_{\delta_e}}$ include ground plane influence.

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